Mine Rescue Management

A Concept for Long-Lasting Missions based on
Case Study Analysis and Disaster Management Approaches

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Case Study Analysis and Disaster Management Approaches

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Abstract (English)

Miners trapped underground at great depths can require long-lasting rescue missions of unknown dimensions. However, common tasks for today’s mine rescue teams mainly cover short-term fire-related incidents and first aid. Since European mining is going to greater depths than before, mine rescue needs innovative approaches for future challenges that will arise. Thus, this thesis develops a Mine Rescue Management (MRM) concept to increase preparedness for an efficient response to long-lasting entrapments.

An analysis of current European mine rescue as well as a risk assessment regarding possible entrapment scenarios in modern mining operations give the scope of this thesis. A database of 56 major mine rescue missions has been compiled and a quantitative analysis proves the relevance of research.

In the main part of this thesis, six single case studies are prepared with qualitative methods followed by a multiple case study analysis. Systematic lessons learned provide a first input for the MRM concept. Identified gaps and weaknesses in mine rescue are then met by a transfer of approved disaster management principles. Together, the two pillars – the case study results as well as the adapted disaster management principles – allow a definition of MRM. This management concept gives comprehensive instructions regarding planning, response, and learning.

The tripartite MRM concept has the potential to improve the preparedness of today’s mine rescue for a complex mission to rescue miners trapped underground.
Abstract (German)


Sowohl die Betrachtung der heutigen Strukturen im europäischen Grubenrettungswesen als auch die Analyse moderner, untertägiger Abbauverfahren belegen einen entsprechenden Forschungsbedarf. Eine eigens erstellte Datenbank, die 56 repräsentative Fälle umfasst, wird statistisch ausgewertet und bestätigt ebenfalls die Relevanz des Szenarios langandauernder Verschüttungen.


Die im MRM zusammengetragenen Empfehlungen haben das Potenzial, das heutige Grubenrettungswesen besser auf komplexe Rettungsmissionen verschütteter Bergleute vorzubereiten.
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1 Introduction

In the wake of import dependencies and critical raw materials, domestic European mining activities play a crucial role to secure future supply of mineral raw materials to the European industry. With respect to underground mining, more than 350 mines are currently operating within the European Union. Sweden, Finland, Bulgaria, and Slovakia are major players in metal mining. Germany is leading in salt mining while Poland possesses the most coal mines. Austria, Italy and the UK are leading in industrial minerals and aggregates. Together, these mines contribute to a diversified supply of raw materials to the European economy. Research and innovative technology are crucial to maintain domestic mining activities, both economically and safe, in the future.

After centuries of mining, a major challenge for the underground mining sector can be seen in the increasing depth of operation. Great depths, also seen as a global trend, considerably influence underground mining in more than one field. The most important issues are related to the safety and health of the mine workers. The increasing depth of a mine not only causes day-to-day burdens like rock heat, but it also affects emergency situations: In a deep mine, escape-ways for the workers to surface increase. The same applies for the increasing distance between mine rescue teams and the underground workplaces.

Under certain circumstances, escape-ways can become fully blocked. Resulting long-lasting entrapments of miners alive are a rare but considerable hazard in deep mining. Successful rescue missions like the “miracle of Lengede” (Germany 1963) or the 69-day rescue of “los 33” in Chile 2010 got world-attention. Transferring such scenarios to mining operations at great depths of 2000 m or more leads to rescue missions of unknown dimensions.

Creating strategies to rescue miners from great depths, establishing international aid, assembling the logistics of a rescue mission that possibly lasts several months, taking care of the miners’ families, or reporting to the world press are challenges that go beyond the capacities and guidelines of today’s mine rescue. For the scope of this thesis, especially this management focus within the large field of mine rescue is of interest. Thus, the following work develops a Mine Rescue Management (MRM) concept that increases the preparedness
of European but also international mining companies and their rescue teams for the scenario of long-lasting entrapments.

While European mining can be classified as homogenous in the overall application of modern technology, the different mine rescue philosophies and capacities differ considerably. The subsequent chapter 1.1 will introduce mine rescue in Europe. However, European mine rescue does not present itself in a uniform way but is different from country to country. Afterwards, chapter 1.2 gives a brief overview of the current state of international research and best practice in mine rescue while already putting focus into long-lasting entrapments. Finally, chapter 1.3 will introduce the actual approach of this thesis and the outline of the main chapters.

1.1 European Mine Rescue

An analysis of European underground mining and mine rescue activities has been done (Lehnen et al. 2013b) to identify major players in European mine rescue. Regarding all EU-membership countries, three groups can be distinguished:

- Belgium, Croatia, Cyprus, Denmark, Latvia, Lithuania, Luxemburg, Malta, Netherlands and Slovenia are countries with currently no or almost no underground mining and thus can be excluded from further evaluation.

- Bulgaria, Greece, Italy, and Portugal are countries with some underground mining activity but without public information available on their mine rescue organization.

- Austria, Czech Republic, Estonia, Finland, France, Germany, Hungary, Ireland, Poland, Romania, Slovakia, Spain, Sweden, and the UK are to be seen as the major players in European (underground) mine rescue.

The qualities of national mine rescue for this last group of countries have been examined (Lehnen et al. 2013b) with respect to legal frameworks, organizational structures and bilateral cooperation.

In its Directive 92/104/EEC for the mineral-extracting industries, the European Council has given general standards as a legal framework for health and safety in mining. With respect to mine rescue, the subsequent requirements for European mining companies are explicitly given:
1. **Introduction**

- emergency communication systems,
- underground workforce accounting,
- trained rescue workers, and
- mine rescue equipment.

National mining laws adapted these requirements. Furthermore, the national regulations comprise more detailed and individual mine rescue philosophies: Mutual aid between domestic mining companies is obligatory in Austria, Czech Republic and Germany. Austrian, Czech, Estonian, German and Polish mine operators further have to make emergency response plans.

Mandatory financial support to centralized mine rescue stations are state of the art in Austria, Poland, and the UK. Such stations provide training facilities, special equipment and professional response teams. In Spain, only coal mines have to make arrangements with such a mine rescue station whereas in Germany it is the entrepreneur’s decision to join an existing mine rescue station or to maintain one on its own. (Lehnen et al. 2013b)

Some national mining laws additionally set minimum standards with respect to the number of rescue personnel for every mine. This is 5% of the underground workforce in the Czech Republic and Ireland and 2% of the employees in Romania (Griffin et al. 2008; Gaman and Pupazan 2007). In the UK, at least two fully-equipped mine rescue teams have to be guaranteed for each mine whereas German coal mines require a minimum of ten teams (Jones 2005; Hermülheim and Roehl 2014). Across Europe, each team usually has 5 members including 1 captain.

As a direct result of the different legal requirements, also the national organization of mine rescue differs within the EU. Most European underground mines possess corporate, voluntary rescue teams. However, in Sweden and Finland, local firefighting brigades provide emergency response to underground mine workings. This is comparable to France, where former coal mine rescue structures merged with the civil rescue services.

Austria, Germany, Ireland, Romania and the Czech Republic have established central bodies to coordinate international cooperation, research, mutual aid, or equipment databases in the field of mine rescue. The real response capacities are provided by the mining companies.
In contrast, Slovakia and the UK have privatized mine rescue services and each mine operator has to pay obligatory fees for a professional coverage. Poland and Hungary have a bipartite system. On the one hand there are professional rescue brigades with a background in hard coal. On the other hand, each mining company maintains own rescue teams as well.

The Irish mine rescue is widely characterized by the different traditions of the operating international mining companies of Canada, South Africa, United States, Sweden or the UK. The mines share mutual aid agreements. The newly established Irish Mine Rescue Committee hosts annual joint mine rescue trainings. The committee also sets standards and fosters exchange with the authorities and other national and international rescue organizations. (Griffin et al. 2008)

Nowadays, **international cooperation** in mine rescue mainly is possible in two different ways:

- Bilateral cooperation (frequently based on personal contacts) is the predominant form with respect to real mutual aid or technical cooperation.
- Institutionalized cooperation by multinational networks provides platforms for an exchange of know-how and experiences during conferences, workshops, and meetings.

Today, especially the mentioned national platforms establish connections to their equivalents within the EU. Bilateral cooperation is widely spread and cultivated by individual as well as structural connections. Particularly strong bilateral cooperation that has been identified is shown in the subsequent Figure 1. The resulting network accordingly identifies Austria, Czech Republic, Poland and Germany as being satisfactorily linked in European mine rescue cooperation. However, there is still no comprehensive, institutionalized European cooperation.

![Figure 1: Bilateral Cooperation in European Mine Rescue (after Lehnen et al. (2013b))](image-url)
On a global scale, an international platform has been established with the International Mines Rescue Body (IMRB) since 2001. Every two years, a member country hosts a conference to allow the exchange of experiences and know-how on national organization, training, equipment, and new technical solutions. Also international competitions are hosted to allow active exchange of the mine rescue teams. Current EU-members of the IMRB are Austria, Czech Republic, France, Germany, Poland, Romania, Slovakia, and the UK.

Concluding, the analysis of European mine rescue shows large differences within the countries’ legal frameworks and organizational approaches. Not many standards are set by European law, albeit national institutions still dominate mine rescue. Currently, there is only limited bilateral cooperation in the EU. The IMRB currently has to be seen as the first international organizational framework that provides a network for mine rescue. Thus, there is currently no European mine rescue. There are strong but heterogeneous capacities; however the technologically homogenous European mining industry has no joint access to them.

1.2 Current State of Research

Long-lasting mine rescue missions can only be seen as usual practice when it comes to the inertization of extensive coal seam fires. But the long-term effects of this type of incidents are not life-threatening. In fact, such missions are conducted to protect assets like equipment, coal fields or the underground mine as such.

Common routines for mine rescue teams are fire-fighting, hazardous gases, and first aid, as stated in different handbooks (e.g. Workplace Safety North (WSN) (2011), Hermülheim et al. (2007), Ramlu (2007), Enright and Ferrier (2014)). However, such guidelines do not provide concepts for long-lasting mine rescue missions for miners trapped alive. Regarding this rare scenario, Dittrich and Nemitz (1968) published an article which comprises some entrapment-specific instructions. It mainly consists of lessons in the wake of the Lengede incident and represents the state of technology of the 1960s.

Research in mine rescue predominantly puts into focus the technological applications and new equipment for mine rescue teams like breathing apparatus and communication
technology. The response itself or the management of rescue missions is not a classic field of academic research. Mine rescue as such is mainly based on experiences and training. EU funded research was done in the 1970s regarding underground drilling applications for short-distance entrapments (Grisard et al. 1981). At the same time, a U.S. study defined needs for research by an analysis of fatal mine disasters (Commission on Sociotechnical Systems, National Research Council 1981). Subsequent NIOSH research was dedicated to psychological aspects of escape and rescue from coal mines (Alexander et al. 2010). Thus, a gap has to be seen in contemporary research on long-lasting rescue missions for miners trapped alive underground.

With respect to the evaluation of major mine accidents, especially single investigation reports on mine rescue missions are available in Western countries. However, by their very nature, they put into focus the causes of such incidents. Examples to be stated here are the reports on the entrapments of Beaconsfield (Melick 2007) and Quecreek (Brady et al. 2003), or the fatal U.S. mine fires of Sago (McAteer et al. 2006) and Upper Big Branch (McAteer 2011). Analyses of the rescue mission as such are rare compared to such root-cause analyses.

Regarding analyses on the actual response, only some single incident reports with special focus on certain aspects of the rescue have been published. With respect to drilling technology, Müller-Ruhe (1998) made an analysis on Lassing (Austria, 1998) as Dittrich (1963) did for Lengede. Regarding management phenomena like leadership, Jordán et al. (2011) reviewed the Chile 2010 rescue while Hersche and Wenker (1999) put focus into Lassing. Liebau (1965) described medical lessons from Lengede, e.g. in overpressure and malnutrition. However, there is a gap regarding systematic multi-aspect studies. The same applies for international multiple case studies. Not many comparative studies are on national level; e.g. Hopkins (2000) for two Australian mine incidents or Dittrich (1964) for German experiences with rescue drilling applications.

Another large gap is a comprehensive, global database of major mine rescue missions. On the internet, there are certain lists and rankings regarding specific records or scenarios of mine accidents and entrapments. But they are all limited to certain countries, time frames, commodities, or other criteria. Furthermore, such lists only comprise a few figures like year
and name of mine. There is no detailed database that compares the majority of past long-lasting entrapments.

Preparedness in mine rescue by guidelines and standards usually comprises so-called Emergency Response Plans. Launhardt (2001) and Mallett et al. (1994) provide good examples of today’s best-practice. However, such planning commonly applies on short-term emergencies. Long-lasting disasters\(^1\) or entrapments have to be seen as rare and unique scenarios that require spontaneous and individual tactics so far.

The subsequent chapter 1.3 will introduce the approach of this thesis. In the further progress, qualitative case study research and disaster management will be introduced and transferred to mine rescue. These independent scientific areas will be separately introduced regarding their state of research and scientific literature in chapters 4.1 and 5.2.

### 1.3 Approach and Structure of the Thesis

As stated in chapter 0, the technical scope of this thesis is long-lasting entrapments of miners underground. Thus, it regards mine rescue in its truest sense because such type of missions put into focus the saving of life and not the recovery of assets. Chapter 2 systematically derives and narrows down the scenarios of being trapped underground. Assessing risks in mining gives possible causes of such incidents. This is followed by a transfer to the above introduced trend to great depths. Finally, an analysis of modern mine layouts (or mining methods) justifies again the relevance of the conducted research.

Chapter 3 develops a comprehensive database of past corresponding mine rescue missions. A quantitative analysis of the data allows identifying trends as well as benchmarks out of the given incidents. Thus, the database allows learning lessons from the past which is the first step of the bipartite approach of this thesis: Case studies from mining as the one pillar and transfers from disaster management principles as the other pillar lead to the final definition and development of the Mine Rescue Management (MRM) concept.

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\(^1\) Definitions which distinguish between emergencies and disasters are provided in chapter 5.1.
Chapter 4 selects suitable missions out of the database for a full case study analysis. This qualitative scientific method allows systematic learning. First, six selected single case studies are conducted. Especially the coding method contributes to the identification of positive and negative strategies. The single case studies are then processed by a multiple case study analysis which leads to a list of qualitative lessons learned.

The second pillar of MRM is the transfer of disaster management principles to the specific needs of mine rescue. Chapter 5 provides a look on disaster management principles. They are systematically selected to fill gaps which have been identified in the case study analyses of major mine rescue missions before. Afterwards, the suitable principles are transferred to the specific needs of mining.

Chapter 6 compiles both the results of the case studies as well as disaster management principles. After a definition of MRM, this innovative management concept is introduced in more details. They follow a tripartite approach of planning, response and learning. The subsequent Figure 2 summarizes the approach of the MRM concept and revisits selected chapters: Mine rescue in general is narrowed down to the specific scenario of long-lasting entrapments. Then, two pillars of case studies and disaster management build the basis for the final MRM concept which meets the needs of the initial challenge of trapped miners.

Figure 2: Approach and Structure of the Thesis
Chapter 7 concludes the thesis’ work. First, it conducts a discussion about the results with respect to current trends in mining and mine rescue. Then, a perspective view is given regarding the future relevance of this work and possible follow-up studies. The thesis closes with a short summary in chapter 8.
2 The Scenario of Long-Lasting Entrapments

Mine rescue covers a large range of tasks, technology and organizational forms. Within the scope of this thesis, long-lasting entrapments of miners underground are the focus scenario. Chapter 2 clearly defines this scenario and shows its importance for future underground mining at great depths.

First, major hazards in underground mining are identified through literature review and an own international survey (2.1). This risk analysis is dedicated to references from the field of mine rescue. The identified major hazards are possible causes for the focus scenario. In a second step, chapter 2.2 shows a classification system which adds the location of such incidents as a new dimension. Taking both, the location and the different major hazards into consideration, certain scenarios remain having the given long-lasting character. Finally, chapter 2.3 analyzes today’s most important underground mining methods with respect to specific locations that allow for the pre-defined scenario. As a result, the coincidence of specific, identified circumstances (hazards, locations, mining methods) can lead to long-lasting entrapments of miners underground. This scenario requires the management of complex rescue missions.

2.1 Major Hazards in Mining

In order to deduce the thesis’ scenario of miners trapped underground, major hazards in mining are first to be identified. Their assignment is based on a literature review as well as an own international survey.

Major hazards in underground mines have been subject to a large range of scientific publications for centuries. Since this thesis puts into focus the rescue of miners alive instead of the technological or organizational prevention of accidents, mainly risk-assessing studies from the field of mine rescue were considered for the following literature review. Figure 3 gives an overview on how frequently certain causes of major accidents or mine disasters were
given in the mine rescue related publications\(^2\) that give overall views on major hazards in mining.

![Figure 3: Hazards in Mining, based on a Mine Rescue Literature Review](image)

Fire and rockfall are given in each related publication followed by explosions and inundations (78% each). Hazardous gases and outbursts are seen as causing factors by almost one in two publications whereas mobile equipment is mentioned less frequently when it comes to major mine disasters.

In order to prepare an international workshop on mine rescue in Beijing 2011, the H&S-supplier Dräger and the central mine rescue station for western Germany conducted an international survey. I have statistically evaluated and extended it in 2012. Altogether, 36 underground mines\(^3\) representing important modern mining countries\(^4\) have participated. One of the 101 questions examined the primary risks the participants face at their underground

\(^2\) Especially Budzilowicz et al. 2003, Brnich, Jr. and Kowalski-Trakofler 2010, Iannacchione et al. 2007, Spencer et al. 2000 and Maier 2009 provide comprehensive views on the cause of major mine accidents and mine disasters. Further sources were IMRB presentations from Francart 2007, Klouda et al. 2009 and Buchanan and Proud 2009. As mentioned above, all references were taken from the scientific field of mine rescue.

\(^3\) The represented groups of commodities are precious metals (51%), base & ferrous metals (34%), coal (26%) and others (6%).

\(^4\) Mine operators from Australia, Canada, South Africa, the United States, Sweden, Germany and the Czech Republic participated.
operations. Figure 4 shows the possible answers (multiple choice; more than one answer and comments were allowed) and the frequency of their responses.

94% of the participants named fire and rockfall as the major hazards in their underground mines followed by hazardous gas related risks like carbon monoxide (88%), O₂ deficiency and ventilation failures (76% each). Inundations were mentioned by half of the participants.

Thus, a compiled list of the major hazards in underground mines – based on both the former literature review as well as the statistical survey – would comprise

- fire,
- rockfalls,
- hazardous gases,
inundations,
• explosions, and
• outbursts.

A description of these major hazards follows:

**Fire.** Equipment fires and spontaneous combustion can be distinguished as two principal types or causes of underground mine fires.

Electrical or mechanical equipment can cause ignitions by friction or glowing parts. For mobile equipment like LHDs or trucks, brakes can heat up during operation. But also other rubbing of loose parts against each other can ignite a fire. Damaged parts of equipment or overloaded conveyor belts are typical sources for such means of friction heat. (Spencer et al. 2000)

Spontaneous combustion of coal is the result of an exothermic reaction of coal with adjacent air. Oxygen gets absorbed, while CO and CO$_2$ are released under increasing temperatures of up to 230°C. (Spencer et al. 2000) Spontaneous combustion is also known for pyrite ores and can cause long-lasting mine fires. In contrast, burning mobile equipment can usually be seen as a local and temporary incident. Nevertheless, the resulting smoke can affect larger parts of the mine through the ventilation system. (Lehnen et al. 2013a)

**Rockfalls.** Rockfalls comprises the loosening of some smaller or larger pieces of rock and is a severe threat for underground mine personnel. Causes for rockfalls are (unexpected) poor rock conditions, insufficient roof support (because of inadequate planning or corrosion) and seismic events (Collier 2003). While a mine roadway is still passable after minor rockfall, a major roof collapse can cause a permanent blockage of underground drifts. Such outbursts or failures of entire structures of the mine are usually the result of rock stresses caused by advanced mining stages and increasing depths of the underground workings (Wagner 2010).

**Hazardous gases.** Both natural (e.g. outbursts) and technical processes (e.g. blasting) can release hazardous gases to the mine’s airflow. A failure of the ventilation system or a sudden outburst can lead to hazardous concentrations of gases. At certain concentrations, some gases can be poisonous, combustible or explosive. However, miners could still
apply self-contained breathing apparatus (SCBA) to travel parts of the mine that are contaminated by poisonous gases. (Lehnen et al. 2013a)

**Inundations.** Water goes into the mine from surface, strata and the underground workings themselves (both active and abandoned). Mine drainage systems handle the regular influx. In contrast, sudden inrushes of water or mud, e.g. as a result of failed barrier pillars to adjacent flooded mines or surface ponds, are a serious threat to miners. Comparable to an explosion, a high quantity of energy is released in seconds or less and can destroy key infrastructure. In a flooded mine, the only chance of survival is in air pockets that possibly form in inclined openings of the mine under overpressure. (Ramlu 2007; Maier 2011)

**Explosions & Outbursts.** In an underground mine, explosions of gas (e.g. methane), liquids (e.g. diesel) or dust (e.g. coal or sulphides) can occur. An outburst is a sudden release of rock stress by means of a large inrush of rock or gas into mine openings. (Ramlu 2007) Both, explosions and outbursts, are hazards by means of fast releases of energy in a short time span. Further consideration in this thesis will only be given to the longer lasting results, which are again

- fire,
- rockfalls,
- hazardous gases,
- inundations.

Having identified these four major hazards, they are further developed in chapter 2.2. A classification system is made to consider these challenges at great depths in two groups of possible locations for such incidents.

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5 Secondary explosions have to be considered as a serious threat as well – especially for mine rescue teams going underground to fight the outcomes of the initial one. (Lehnen et al. 2013a)
2.2 The Challenges of Great Depths

Having identified the major hazards in underground mining, they need to be brought into taxonomy to further specify the scope of this thesis. For this purpose, a classification system is developed to answer the question, under which circumstances these hazards can cause a long-lasting entrapment of miners underground. Besides the location of the equivalent incident, the scheme also takes the special challenge of mining at great depths into consideration.

The classification system for major mine emergencies was created in 2012 and first published in 2013 (Lehnen et al. 2013a). The subsequent Figure 5 shows a modified version. This classification system will be explained in the following.

Level III of the system shows the four major hazards – inundation, rockfall, fire and gas – as they were given in chapter 2.1. In a prior step (level II), they are projected on two general types of locations within the underground mine: “Dead Ends” and “2 Escape-Ways”. Dead ends, by nature, provide only one means of escape to the miner. This can be seen as an unusual case in modern mining (see 2.3 for a full description). Usually and by law, most of the underground work places provide at least two different means of escape. They are normally ventilated by the main air flow of the mine.
All scenarios that have a relation to this last type of location are green-colored in the diagram: If one hazard affects one of the two escape-ways available, the area becomes only “partly sealed off”. In such a case of emergency, the miners will immediately use the second escape-way. This regular evacuation strategy\(^6\) of the mine is called “self-rescue” (see level V within the classification system).

If such a second means of escape is not available – as in a dead end – the four major hazards cause more complex rescue missions. When the only escape-way becomes affected by fire or hazardous gas, the area behind becomes “temporary sealed off” (yellow colored scenarios in the classification system). Fire and gas related incidents are usually limited in time (see above):

A fire can be fought by the miners themselves or by specialized mine rescue teams. In the last case, temporarily trapped miners could wait in sealed rescue chambers (so called “aided rescue” strategy on level V). An accumulation of hazardous gases can usually be removed by the mine ventilation system. Again, eventually trapped miners could proceed to rescue chambers or escape by using special self-rescuers\(^7\) (again “self-rescue” on level V).

Clearing collapsed or flooded parts of an underground mine are much more complex rescue missions. If major rockfalls or water inundations take place behind miners in a dead end, their location becomes a “long-lasting sealed off area” (red colored scenarios). A self-rescue is not possible and a complex mine rescue mission has to be conducted to first supply and second release the trapped miners.

Having identified these three overall types of scenarios (green, yellow and red), the bottom level VI of the classification system transfers these types of major mine emergencies to the emerging trend of mining to great depths. No matter if a mine grows and develops in a horizontal or a vertical direction, corresponding escape-ways for the miners (green) and travel

\(^6\) Self-escape, whenever possible, is the approved evacuation strategy for most underground mines. Not many mining companies train their underground personnel to proceed to refuge chambers in any major emergency situation.

\(^7\) Self-rescuers provide oxygen – usually generated by a chemical reaction – or just put the ambient mine air through a filter. In most mines, they are a belt-worn personal item for each miner and can be donned to enable a safe escape if dust, smoke or other hazardous gases are present. The United States’ National Research Council provides a comprehensive over-view on self-rescue technology (National Research Council 2013, pp. 3–10-3–12).
times for the mine rescue teams (yellow) respectively become longer. But technological development in mine rescue can cope for the arising challenges:

For self-rescue, the capacity of self-rescuers can be increased or special rescue chambers can be strategically integrated into the evacuation procedures. They work as a change-over station for new filters or cartridges and allow a rest during a long-lasting escape. For aided rescue, the capacity of rescue chambers and their oxygen supply can be increased as well. Mine rescue teams can also build up safe change-over stations underground, which are called “fresh air bases”. These coping strategies allow for the green and yellow colored scenarios the adoption of nowadays usual procedures of experienced mine rescue teams – even at great depths.

In contrast to self-escape and fire-fighting, the rescue of miners trapped underground – especially behind collapsed rock or huge amounts of water (red colored scenarios) – are rare and non-regular missions. Predominant rescue strategies are on the one hand the drilling of holes for searching, supplying and rescuing the trapped miners and on the other hand the pumping of water. Here, rescue time is life-critical but can significantly increase with the depth of the underground workings.

Thus, long-lasting entrapments of miners underground caused by major rockfall or water inundation have to be seen as a major challenge for mine rescue at great depths (red colored scenarios). Besides technological issues, the overall dimension of the corresponding rescue missions increases with the time of the operation. Thus, this thesis puts into focus the management of such a rare but complex (or LP-HC) mine rescue mission.

As told before, miners are usually trained to escape during emergencies and nowadays mine planners usually design secondary escape-ways for all parts of underground mine layouts. Chapter 2.3 evaluates modern mining methods for the occurrence of dead ends because they are the only points that pose the risk of such long-lasting entrapments.

---

8 When the escaping miner reaches a non-affected (“fresh”) air flow, there is no more life-critical influence of great depths to the further evacuation of the mine. If told to do so, the miner can then just doff the self-rescuer and regularly leave the mine (Lehnen et al. 2013a, p. 4).
9 In the fields of the transportation of hazardous materials or the operation of nuclear power or chemical plants, “LP-HC” describes Low-Probability, High-Consequence events (see Beroggi, Giampiero E. G. and Wallace 1998, p. 1).
2.3 Analysis of Modern Mine Layouts

The classification system of major hazards developed in chapter 2.2 tells that dead ends are the only locations in underground mines where the thesis’ focus scenario of miners trapped underground can occur. Distinguishing underground mine development and underground mine production, the subsequent chapter systematically screens the two steps of underground mining for possible dead ends to consider.

Mine development (MD) comprises all works performed

- to connect the surface with the underground (primary MD),
- to develop the deposit underground (secondary MD) and
- to prepare parts of the deposit for the actual mine production (tertiary MD).

Horizontal, inclining and vertical openings can be distinguished. Vertical MD as by mine shafts, ventilation raises or ore passes hardly provide chances of survival after major roof collapse or inundation. Hence, only the classical MD works of road heading (or tunneling) can be considered for the corresponding scenarios.

![Figure 6: Entrapment-Scenario Road Heading](image_url)
Depending on the purpose, such mine drifts can become very long before they reach or get connected to other parts of the mine.\(^\text{10}\) As long as they are driven up, they have to be classified as a dead end providing only one means of escape by nature. Figure 6 illustrates a water inundation as one of the two possible causes for entrapments in such a road heading operation. As told before, inundations can only be survived in over-pressured air pockets that require an inclined drift.

MD and especially road heading is necessary for all underground mines. Hence, the previously shown scenario has to be considered for all modern mining methods. When MD has prepared the deposit, the actual mining (or production) starts and applies different mining methods that are in line with the local geological (and other) requirements. The subsequent Table 1 shows the ten major mining methods after the reference work of Hartman and Mutmansky (2002). They are grouped by their way of roof support. In the following they are screened for eventual occurrences of dead ends. MD is not included again in this evaluation.

<table>
<thead>
<tr>
<th>Unsupported</th>
<th>Supported</th>
<th>Caving</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room-and-pillar mining</td>
<td>Cut-and-fill stoping</td>
<td>Longwall mining</td>
</tr>
<tr>
<td>Stope-and-pillar mining</td>
<td>Stull stoping</td>
<td>Sublevel caving</td>
</tr>
<tr>
<td>Shrinkage stoping</td>
<td>Square-set stoping</td>
<td>Block caving</td>
</tr>
<tr>
<td>Sublevel stoping</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Shrinkage stoping, stull stoping and square-set stoping do not play a role in modern mining (Hartman and Mutmansky 2002, pp. 339, 365). Thus, they are excluded for further evaluation. In contrast, stope-and-pillar mining is an important mining method. But since its working principle is equivalent\(^\text{11}\) to the room-and-pillar mining, it is not considered separately here.

At the production site, the important mining methods of room-and-pillar mining (R&P), block caving and longwall mining do not show dead ends. The typical R&P-grid provides multiple escape-ways for the miners. The actual production is comparable to MD and especially at

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\(^{10}\) As an example, exploration drifts are possibly several kilometers long and do not have one crosscut to other drifts. They are only used by exploration drill rigs and not part of the regular mining logistics.

\(^{11}\) Compared to room-and-pillar mining, in stope-and-pillar mining, pillars are more irregularly shaped, the openings (“rooms”) are higher than wide and it is not applied in coal. (Hartman and Mutmansky 2002, p. 333)
the face these steps can hardly be distinguished. MD also plays an important role for block
caving operations. But once the complex underground infrastructure is developed, the ac-
tual mining work principally comprises ore mucking at draw points which all provide at least
two directions for escape in case of emergency. Longwalls are always mining between two
parallel drifts. These development openings guarantee two escape ways out of the longwall
as well.

Sublevel stoping is made to mine steep hard rock deposits of moderate thickness. The
mining method creates an open and unsupported stope that is not accessed by miners at
any time. Sublevels are driven up to enable production drill & blast at the stope borders.
These sublevels can be classified as dead ends although they might still have air flow through
the stope after a roof collapse has cut-off the only means of escape for the miners (see
Figure 7).

Cut-and-fill mining is a mining method applicable to steep hard rock deposits of low thick-
ness – like ore veins. Here, miners go into the opening, which is only a small horizontal slice
(“cut”) of the deposit. Since they are usually mining bottom-up, mined-out cuts are back-
filled to provide a working platform for the subsequent production cycle. This platform usu-
ally has only one access drift to the remaining mine which is usually provided by a ramp. If
this single escape-way becomes blocked by the scenarios given before, miners would be
trapped for a longer time (see Figure 8).
Sublevel caving is one more mining method for steep ore deposits. Here, sublevels are used to undercut the orebody. By blasting and mucking the ore, caving is initiated that causes subsidence up to surface. Comparable to sublevel stoping, these production sublevels are dead ends and could be damaged again. Figure 9 illustrates that the broken material on both sides of the trapped even further complicates this kind of entrapment (compared to sublevel stoping).
• Road heading (as MD work in all underground mines)
• Sublevels (as part of production in sublevel stoping and sublevel caving operations)
• Access drifts (as occurring in cut-and-fill operations)

While MD work is part of all underground mines, the three mining methods of sublevel stoping, cut-and-fill and sublevel caving are mine layouts that are especially designed for steep hard rock deposits.

Generally speaking, especially long single road heading drifts can be seen as the most challenging scenario: They can cause entrapments with long (vertical or horizontal) distances to neighboring openings of the mine or even surface. Sublevels, in contrast, are usually close to other sublevels or transportation drifts. This possibly facilitates a thinkable rescue mission because drilling could be done from the underground instead of surface.
3 Compilation of a Database of Major Mine Rescue Missions

Systematic learning from past missions is a key pillar of this thesis’ approach of mine rescue management. In preparation of the case study analyses, a database of corresponding historic cases has been developed. This database is already a major outcome of this thesis and is described in the subsequent chapters.

Chapter 3.1 sets a clear scope for data collection and inquiries: Only mine rescue missions fulfilling certain criteria of the previously defined scenarios of long-lasting entrapments are subject to the data collection procedure. Chapter 3.2 describes how corresponding cases have been identified and how specific information has been collected. Different types and qualities of documents are to be handled and put through filters carefully.

Altogether, 56 mine rescue missions – or cases – are identified and shortly introduced in chapter 3.3. Referring back to the data collection, chapter 3.4 shows the organization of contents within the database. Chapter 3.5 finally gives an overall quantitative analysis of all cases. Statistical figures enable extrapolation and prediction of dimensions of future mine rescue missions in great depth but are however limited because of the highly individual cases.

3.1 Definition of Scope

As told before, mine rescue covers a large field of rescue, recovery and day-to-day tasks. Hence, the subsequent inquiries need to clearly put into focus missions that correspond to the scenarios which have been given in chapter 2. Three different filters have been developed to guarantee that focus:

- Miners trapped alive
- Long-lasting missions
- Modern mining

Miners trapped alive. Miners being trapped underground are the base scenario for this thesis. The condition “alive” makes the following actions a rescue mission, whereas
searching and collecting dead bodies defines a recovery mission. Mine rescue missions are commonly not stopped as long as trapped miners can still be considered alive. Technical and financial efforts usually do not know limits as long as there is still hope for survival. As a result, only past mine rescue missions that ended up with the successful rescue of miners alive are to be recorded in the built up database.

**Long-lasting missions.** The challenge of mining going deeper and its effects on the overall duration of rescue missions has been derived in chapter 2. The following view into the past will show that not many missions have been conducted in great depths or over long time. Thus, for the scope of this study, “long-lasting” already comprises past missions that lasted more than three days.¹²

**Modern mining.** “Modern” is a relative term. Here, 1950 has been set as the starting point of inquiries. In this time, most industrialized countries grew fast and mechanization made mining techniques and layouts at least comparable to nowadays’ operations. 2014 is set as the last year of review.

These three filters set the scope for the data collection which is given in the subsequent chapter. Only mine rescue missions that fulfill all of these criteria at the same time are to be included into the database.

### 3.2 Data Collection

Data collection is one of the major steps done during case study analysis.¹³ Within this thesis, the data collection and its incorporation into a database of major mine rescue mission functions as a pre-selection of possible cases for the subsequent detailed case studies. The careful selection of cases – as the opposite of random sampling – is a key quality of case study research. (Creswell 2014)

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¹² *Three* is also known to be a life-critical number in survival: As a rule of thumb, humans can survive three minutes without oxygen, three days without water and three weeks without food. (Buzek 2007) Of course, that must agree with a lot of individual conditions. But the way trapped miners survived longer than three days without pre-planned water resources is, however, an interesting point of research for the following case studies.

¹³ The methodology of the case study approach will be introduced in more detail in chapter 4.1.
Two different steps of data collection were conducted: The first step is to identify cases that pass the requirements (the filters defined in 3.1). In a second step, a maximum of information regarding each single mine rescue mission has to be gathered. In other words, the first step makes the database larger in a vertical way, because new mine rescue missions are put on the list. During the second step, the database increases horizontally when more and more information is added to each case.

Searching for major mine rescue missions (step 1), you cannot find one large database. Instead, different institutions and authors provide smaller lists. Depending on the individual interests, these lists can be tables or rankings of only selected mine rescue missions. They can be limited by country or commodity or they are only mentioning certain types of rescue strategies or technologies.

A different procedure of finding cases is to follow references and comparisons within a report that originally describes only one mission or disaster. This makes this thesis’ data collection procedure run through cycles between the given steps 1 and 2. However, all cases identified that are in line with the three filters are included into the database. Then, step 2 does a check for detailed information on each of these cases:

Each mine rescue mission out of the database has been entered into popular as well as scientific databases online. The same step was repeated for each author of the corresponding documents and his or her references. Usable documents could be official investigation reports, mining journals, local newspapers, mine rescue conference papers, minutes of meetings or even novels that were prepared by or with survivors.

The publication and availability of such sources are different from one case to the other. This highly depends on when and where such incidents occurred. Especially the rise of the internet and social media made more information available – even for countries that still have strict information policies. Generally, the variety of document types given above provides valuable variation in opinions and points of view for a single case.

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14 Also on a more general level, the mining industry lacks of providing risk-related databases (Rasche 2012). That is, on the other hand, a good motivation to assemble a comprehensive database of major mine rescue missions within this thesis.
Such use of several (e.g. three) different opinions and views for one piece of information is called “triangulation”. Triangulation is one major principle and advantage of the case study data collection approach (Yin 2014). Literature names some advantages and disadvantages of using such documentations (instead of interviews, field trips, etc.) as a source for case studies:

Table 2: Aspects of referencing documents (compiled after Yin 2014 and Creswell 2014)

<table>
<thead>
<tr>
<th><strong>Strengths</strong></th>
<th><strong>Weaknesses</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable – as the source can be reviewed at any time</td>
<td>Accessibility – comparable sources are not available for each case</td>
</tr>
<tr>
<td>Specific – as the source possibly tells accurate names or numbers</td>
<td>Researcher’s bias – the researcher might not want to include all documents in the case study</td>
</tr>
<tr>
<td>Broad – as the source can describe events and settings over a long time-span</td>
<td>Reporter’s bias – the author of the source with his or her point of view and perception</td>
</tr>
<tr>
<td>Authentic – if written by a participant, wording can be valuable information</td>
<td>Incompleteness – an extensive description of all aspects of interest is usually not found</td>
</tr>
<tr>
<td>Unobtrusive – the researcher decides when to analyze each document</td>
<td>Liability – documents can neither be authentic nor accurate</td>
</tr>
</tbody>
</table>

While benefitting of the strengths, the weaknesses given in Table 2 are met by careful use of triangulation within this thesis. The notation of triangulation for each piece of data is going to be explained in chapter 3.4. Especially the variation of perspectives is helpful during the analysis of a mine rescue mission. Different points of view are provided by media, authorities, the mining companies and the trapped miners themselves:

- **News** (by media) is easily accessible but usually inaccurate because of their fast publication or the non-mining background of journalists.

- **Mining authorities** prepare large investigation reports which are usually published a long time after the incident. Depending on the country, they are freely accessible and provide neutral information that is also used for legal inquiries.

- **Trapped miners** possibly publish novels to process their impressions and experiences. Such information is highly biased but also provides full insights into the survival underground.
• Also the effected mining companies might share reports. Again, this information can be biased but also detailed – for example in technological aspects of the mine and the rescue.\textsuperscript{15}

As mentioned before, all these sources of information need to be handled carefully. But triangulation can provide safe and comprising data. The subsequent chapter 3.3 will give an overview of all cases that have been identified through the data collection shown here.

3.3 Overview of Identified Cases

The data collection identified 56 cases in the given time frame from 1950 to 2014. Taking into account the three filters given in chapter 3.1, all cases describe a mission leading to the rescue of trapped miners alive after more than three days. Three mine rescue missions are divided and counted as two separated cases each because two groups of miners were trapped and rescued independently from each other at any one time:

In Lengede, Germany in 1963, multiple groups of miners were trapped and rescued. Two of them fulfilled the defined filters: Three miners were trapped for eight days and eleven miners were trapped for even 14 days. Correspondingly, the two independent cases are named “Lengede (3for8)” and “Lengede (11for14)” and shown separately in the database. The same applies for “Saxsewell (15for5)” and “Saxsewell (6for10)”, USA 1968, and “Jiaonan (6for4)” and “Jiaonan (1for10)”, China 2010.

The subsequent tables give a short overview of the identified cases. Here, only the groups of country, year, mine name, commodity, scenario, duration\textsuperscript{16}, number of survivors, and the depth of the entrapment are given. The particular scenarios cover major rockfalls (R), inundations (I) and fires (F) following the taxonomy of Figure 5 (see p. 16).

\textsuperscript{15} Kletz (1993) names four causes for a mining company to provide free information about major incidents:
• the moral intention to prevent recurrence anywhere;
• the pragmatic hope to receive such important warnings from other companies as well;
• the economic thinking to make competitors spend comparable efforts into safety;
• the effected public image that concerns the whole industry and can lead to new legislation for all competitors.

\textsuperscript{16} The total duration is measured in rounded up days calculated from the initial event until the final rescue of the last miner alive.
Again for reasons of clarity, this short version of the database has been divided into regional groups, which are Germany, other EU countries, China, U.S., and Other. Each of the subsequent five tables is in descending chronological order.

Table 3 shows nine cases identified for Germany. As mentioned before, the famous “miracle of Lengede” has been divided into two separate cases. Dahlbusch 1955 became famous as well, being the first mine rescue mission using an ad hoc built rescue capsule. This important mine rescue device called the “Dahlbusch bomb” is still referred to today.

<table>
<thead>
<tr>
<th>Year</th>
<th>Mine</th>
<th>Commodity</th>
<th>Scenario</th>
<th>Duration Total [d]</th>
<th>No. of Survivors</th>
<th>Depth [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1969</td>
<td>Emil Fritz</td>
<td>Coal</td>
<td>R</td>
<td>3</td>
<td>5</td>
<td>650</td>
</tr>
<tr>
<td>1963</td>
<td>Lengede (3for8)</td>
<td>Iron Ore</td>
<td>I</td>
<td>8</td>
<td>3</td>
<td>80</td>
</tr>
<tr>
<td>1963</td>
<td>Lengede (11for14)</td>
<td>Iron Ore</td>
<td>I</td>
<td>14</td>
<td>11</td>
<td>55</td>
</tr>
<tr>
<td>1958</td>
<td>Friedrich der Große</td>
<td>Coal</td>
<td>R</td>
<td>4</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1957</td>
<td>Gustav</td>
<td>Barite</td>
<td>R</td>
<td>5</td>
<td>2</td>
<td>80</td>
</tr>
<tr>
<td>1957</td>
<td>Emil Emscher</td>
<td>Coal</td>
<td>R</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1956</td>
<td>Fröhliche Morgensonne</td>
<td>Coal</td>
<td>R</td>
<td>10</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1955</td>
<td>Dahlbusch</td>
<td>Coal</td>
<td>R</td>
<td>5</td>
<td>3</td>
<td>855</td>
</tr>
<tr>
<td>1951</td>
<td>Neuruhrort</td>
<td>Coal</td>
<td>R</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Besides Germany, also other EU countries became the scene for long-lasting mine rescue missions. Table 4 shows six cases. Lassing, Austria 1998 achieved the world’s attention – mainly in negative ways regarding the chaotic rescue efforts. The last incident fitting the scope of this thesis took place in the Polish Halemba coal mine in 2006:

<table>
<thead>
<tr>
<th>Country</th>
<th>Year</th>
<th>Mine</th>
<th>Commodity</th>
<th>Scenario</th>
<th>Duration Total [d]</th>
<th>No. of Survivors</th>
<th>Depth [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poland</td>
<td>2006</td>
<td>Halemba</td>
<td>Coal</td>
<td>R</td>
<td>5</td>
<td>1</td>
<td>&gt; 1000</td>
</tr>
<tr>
<td>Austria</td>
<td>1998</td>
<td>Lassing</td>
<td>Talc</td>
<td>I</td>
<td>9</td>
<td>1</td>
<td>60</td>
</tr>
<tr>
<td>Poland</td>
<td>1970</td>
<td>Dukla</td>
<td>Coal</td>
<td>I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>France</td>
<td>1964</td>
<td>Champagnole</td>
<td>Limestone</td>
<td>R</td>
<td>8</td>
<td>9</td>
<td>82</td>
</tr>
<tr>
<td>Netherlands</td>
<td>1955</td>
<td>Willem-Sophia</td>
<td>Coal</td>
<td>R</td>
<td>4</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Hungary</td>
<td>1952</td>
<td>Szuhakallo</td>
<td>Coal</td>
<td>I</td>
<td>6</td>
<td>17</td>
<td>75</td>
</tr>
</tbody>
</table>
Table 5 provides one more national view: The United States covers six cases. The last incident occurred in 2002, when the Quecreek coal mine became flooded. The Sunshine silver mine fire of 1972 is the only non-coal incident within the U.S. cases. Furthermore, it is one of only two fire scenarios in which survivors have been rescued after more than three days (together with Chiyu, China 2002).

<table>
<thead>
<tr>
<th>Year</th>
<th>Mine</th>
<th>Commodity</th>
<th>Scenario</th>
<th>Duration Total [d]</th>
<th>No. of Survivors</th>
<th>Depth [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>Quecreek</td>
<td>Coal</td>
<td>I</td>
<td>4</td>
<td>9</td>
<td>73</td>
</tr>
<tr>
<td>1977</td>
<td>Porter Tunnel</td>
<td>Coal</td>
<td>I</td>
<td>6</td>
<td>1</td>
<td>133</td>
</tr>
<tr>
<td>1972</td>
<td>Sunshine</td>
<td>Silver</td>
<td>F</td>
<td>8</td>
<td>2</td>
<td>1463</td>
</tr>
<tr>
<td>1968</td>
<td>Saxsewell No. 8 (15for5)</td>
<td>Coal</td>
<td>I</td>
<td>5</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>1968</td>
<td>Saxsewell No. 8 (6for10)</td>
<td>Coal</td>
<td>I</td>
<td>10</td>
<td>6</td>
<td>24</td>
</tr>
<tr>
<td>1963</td>
<td>Oneida</td>
<td>Coal</td>
<td>R</td>
<td>14</td>
<td>2</td>
<td>102</td>
</tr>
</tbody>
</table>

China accounts for the most identified cases. They are all comprised in Table 6. The almost empty column of “Depth” illustrates that there is no detailed data available for most of the incidents. Also, a high number of unreported cases have to be expected – especially for the time frame before online media emerged.

<table>
<thead>
<tr>
<th>Year</th>
<th>Mine</th>
<th>Commodity</th>
<th>Scenario</th>
<th>Duration Total [d]</th>
<th>No. of Survivors</th>
<th>Depth [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>Junyuan No. 2</td>
<td>Coal</td>
<td>I</td>
<td>17</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>Anllai</td>
<td>Coal</td>
<td>R</td>
<td>4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>Furuixiang</td>
<td>Coal</td>
<td>I</td>
<td>5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>Coal</td>
<td>R</td>
<td>8</td>
<td>2</td>
<td>320</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>Hengtai</td>
<td>Coal</td>
<td>I</td>
<td>7</td>
<td>19</td>
<td>274</td>
</tr>
<tr>
<td>2010</td>
<td>Iron Ore</td>
<td>I</td>
<td>8</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>Wangjialing</td>
<td>Coal</td>
<td>I</td>
<td>8</td>
<td>115</td>
<td>250</td>
</tr>
<tr>
<td>2010</td>
<td>Jiaonan (6for5)</td>
<td>Coal</td>
<td>I</td>
<td>5</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>Jiaonan (1for11)</td>
<td>Coal</td>
<td>I</td>
<td>11</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>Xinquao</td>
<td>Coal</td>
<td>I</td>
<td>25</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>Yongxing Gaogzhuang</td>
<td>Coal</td>
<td>R</td>
<td>8</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>Hantian</td>
<td>Tungsten</td>
<td>R</td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>Zhaojialiang</td>
<td>Coal</td>
<td>R</td>
<td>7</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>
### 3. Compilation of a Database of Major Mine Rescue Missions

<table>
<thead>
<tr>
<th>Year</th>
<th>Mine</th>
<th>Commodity</th>
<th>Scenario</th>
<th>Duration Total [d]</th>
<th>No. of Survivors</th>
<th>Depth [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>Qunfa</td>
<td>Coal</td>
<td>I</td>
<td>5</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>Yangchong</td>
<td>Iron Ore</td>
<td>R</td>
<td>5</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td></td>
<td>Iron Ore</td>
<td>R</td>
<td>5</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>Aiyou</td>
<td>Coal</td>
<td>R</td>
<td>4</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td></td>
<td>R</td>
<td></td>
<td>15</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>Kangli</td>
<td>Gypsum</td>
<td>R</td>
<td>11</td>
<td>1</td>
<td>200</td>
</tr>
<tr>
<td>2004</td>
<td>Chaohua</td>
<td>Coal</td>
<td>I</td>
<td>5</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>Chiyu</td>
<td>Coal</td>
<td>F</td>
<td>5</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>Jianshe</td>
<td>Coal</td>
<td>I</td>
<td>8</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>1996</td>
<td></td>
<td>I</td>
<td></td>
<td>8</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>1985</td>
<td></td>
<td>Coal</td>
<td>R</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1983</td>
<td></td>
<td>Coal</td>
<td></td>
<td>23</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Finally, the subsequent Table 7 shows identified cases in all other non-EU countries. That includes Chile’s 2010 rescue of “los 33”, which is probably the most famous rescue mission in mining history. With a total duration of 69 days it is the longest mine rescue missions for miners alive in history.

### Table 7: Identified Cases in other Countries

<table>
<thead>
<tr>
<th>Country</th>
<th>Year</th>
<th>Mine</th>
<th>Commodity</th>
<th>Scenario</th>
<th>Duration Total [d]</th>
<th>No. of Survivors</th>
<th>Depth [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peru</td>
<td>2012</td>
<td>Cabeza de Negro</td>
<td>Copper</td>
<td>R</td>
<td>6</td>
<td>9</td>
<td>520</td>
</tr>
<tr>
<td>Chile</td>
<td>2010</td>
<td>San Jose</td>
<td>Copper</td>
<td>R</td>
<td>69</td>
<td>33</td>
<td>700</td>
</tr>
<tr>
<td>Australia</td>
<td>2006</td>
<td>Beaconsfield</td>
<td>Gold</td>
<td>R</td>
<td>14</td>
<td>2</td>
<td>925</td>
</tr>
<tr>
<td>Russia</td>
<td>2003</td>
<td>Zapadnaya</td>
<td>Coal</td>
<td>I</td>
<td>6</td>
<td>11</td>
<td>700</td>
</tr>
<tr>
<td>India</td>
<td>2001</td>
<td></td>
<td>Coal</td>
<td>I</td>
<td>6</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>S. Africa</td>
<td>2000</td>
<td>Gold</td>
<td>R</td>
<td></td>
<td>4</td>
<td>9</td>
<td>&gt; 2000</td>
</tr>
<tr>
<td>S. Africa</td>
<td>1993</td>
<td>Kloof</td>
<td>Gold</td>
<td>R</td>
<td>6</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>S. Korea</td>
<td>1982</td>
<td>Coal</td>
<td>R</td>
<td></td>
<td>14</td>
<td>4</td>
<td>244</td>
</tr>
<tr>
<td>S. Korea</td>
<td>1968</td>
<td></td>
<td></td>
<td></td>
<td>15</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Canada</td>
<td>1954</td>
<td></td>
<td></td>
<td></td>
<td>8</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>
3.4 Organization of Contents

The compiled database of major mine rescue missions is Excel-based. Microsoft (MS) Excel is in fact no database management software (like MS Access) but a spreadsheet application. However Excel has been chosen for the scope of this thesis because it provides valuable statistical calculation and visualization tools for the initial quantitative analysis (see 3.5). The dimension of around 56 x 100 cells in the primary spreadsheet (see below) and another six smaller spreadsheets keeps the database manageable even without special framing or interlacing tools as they are provided in MS Access.

The first central spreadsheet contains all basic information of the identified cases. Each line of the table represents one case. Thus, the sheet vertically comprises 56 rows of content. In horizontal direction, all the data is provided for each case. About 100 columns organize the different contents:

As shown in chapter 3.3, basic quantitative (numerical) figures are year, depth, number of survivors and the duration of the rescue mission. Besides this total duration, also other important time frames are recorded:

- Time until notification (warning) of the incident
- Time until the necessary rescue equipment (like drilling rigs) came to the site
- Time until the trapped miners were located
- Time until external supply (like food or medicine) reached the miners

More numerical data has been collected regarding the dimension of the confined space underground (void, height, length; volume), the numbers of rescue personnel and journalists on site, and the number of drillings conducted during the rescue mission (further distinguishing pilot holes, drainage holes and rescue holes). Binary information (true/false) has been used to show

- if access to the underground was still available to the mine rescue teams;
- if the trapped miners had supply of fresh air; and
- if international cooperation took place.
Besides quantitative figures, also qualitative data (in words) is recorded in different columns. Basic information like country, mine, commodity, and scenario has already been introduced in chapter 3.3. Further information regarding the mine is the mining company (operator and owner), the mining method and the geology (especially overburden strata which highly influence possible drilling efforts).

More qualitative data regarding the incident itself comprises its initial cause and the resulting location of the trapped miners underground. With respect to the related mine rescue technology, the methods of locating and rescuing is recorded as well as explicit information about lagging and accelerating factors of the rescue missions. Also explicitly mentioned positive and negative lessons of the rescue and the potential role of previously installed preventive measures (like refuge chambers) are recorded.

All of this information is kept in the first spreadsheet of the database. The second spreadsheet contains calculations and diagrams for the quantitative analysis which will follow in chapter 3.5. Further spreadsheets provide details on specific aspects of the mine rescue missions:

- What are possible strategies to survive without supply from surface?
- What supply is sent underground as soon as the trapped miners are reached by a small diameter pilot drill hole?
- What are psychological effects and countermeasures during the entrapment?

Another separate spreadsheet provides a detailed drilling database. Wherever information was available, each single drill hole of the different rescue missions is recorded here. Corresponding data for each hole is

- its case, name and purpose;
- its diameter(s), length and duration;
- the applied technology, the drilling company; and
- a first evaluation (failed, successful, ...).

Each of the columns with regards to quantitative or qualitative content in each of the spreadsheets is followed by a column named “Q”. This column provides the original
references to each cell containing any kind of information. More than 1,300 references regarding mine rescue have been collected and are managed in a separate literature database which is again Excel-based. Here, each reference is assigned to an individual serial “Q” number.

Thus, the “Q” columns in the mine rescue mission database only contain numbers. Whenever one piece of information is referenced by at least three different sources, the corresponding “Q” cell is colored in bright yellow. This indicates successful triangulation, as introduced in chapter 3.2.

As mentioned before, the Excel database only contains numbers or short qualitative information. All original text passages or quotes are stored in a MS Word transcript. Figure 10 gives an overview on how the different databases given above interact and how they contribute to the analyses of this thesis. Data in Excel is colored in green, Word in blue and the simple MS Windows filing in yellow:

The main part of the database will be analyzed quantitatively in the subsequent chapter 3.5. More contents of the transcript are processed in the qualitative case study analysis in chapter 4. The selection of these cases is again based on the quantitative analysis.
3.5 Quantitative Analysis

As introduced in the previous chapters, the compiled database of major mine rescue missions contains both quantitative and qualitative data. The current chapter 3.5 makes the first step of analysis. Here, a quantitative approach has been chosen to guarantee an objective access by explicit evaluation (Rasche 2012, p. 17) before continuing with a deeper and qualitative analysis of selected case studies in chapter 4.

Accordingly, this chapter provides a quantitative analysis of all 56 cases in the database. All quantitative analysis steps are calculated and visualized by MS Excel tools, which was again the primary reason for using Excel for the database itself. In the first steps, quantitative data is subject to the analysis. The second part of this chapter also makes quantitative analyses of qualitative data of all cases, e.g. by simply counting words in specific columns.

To start with basic quantitative data (year of the incident), Figure 11 shows the distribution of all cases (blue line and dots) over the given time:

![Figure 11: Annual Distribution of Cases](image)

Showing roughly one case for each year in the 1950s and 60s, a fall follows in the 1970s and 80s. Starting in the 1990s, a strong increase occurred in the new century. Especially China contributes to these high figures. As already described in the last chapter, this has possibly a relation to the increase of information flow now available on the internet.

On the other hand, no cases were recorded in 2013 and 2014 as the last years of observation. As a conclusion, no clear trend can be seen but the relevance of the conducted
research becomes obvious: The 21st century, where increased safety provisions and improved escape-way systems could be presumed, has already faced more cases of long-lasting entrapments than the second half of the 20th century.

To simultaneously put into focus the European mining industry, each case that occurred in an EU-country has been indicated by a yellow star in the chart. The accumulation of incidents in the 50s and 60s is almost exclusively covered by European cases. This is possibly again because of data availability, but nevertheless, incidents reoccurred in the recent past with a frequency of roughly one case for every decade (Austria 1998 and Poland 2006).

The prediction of the dimension of future (mine rescue) missions is an important use of quantitative records (Kletz 1993). The total mission duration is obviously a key figure regarding the survival of trapped miners. One would intuitively look for a correlation between the depth of the miners’ confinement and the required rescue time. Accordingly, Figure 12 shows all 56 cases horizontally and provides (if available) two numerical values vertically above each case: The depth (left axis in meters) is shown by a blue triangle. A green circle symbolizes the total duration of the corresponding rescue (right axis in days).

**Figure 12: Relation of Depth and Total Duration**

Obviously, there is no clear trend or correlation between depth and duration. Especially the extreme cases’ circles and triangles diverge widely on the vertical scale: Case 39 represents a roof collapse in a South African gold mine in 2000. At more than 2 km, it is the deepest
recorded case of miners trapped underground. However, it took “just” four days to bring them back to surface. In contrast, Chile 2010 (case 3) is, by far, the longest mine rescue mission: Rescuing the 33 miners from a depth of about 700 m took 69 days.

Causes for this distribution are found in the high individuality of the cases. One important property that highly influences the total duration of a case is whether any access to the underground is still open. For example, starting drilling underground instead of on surface can substantially decrease the distance to the trapped miners. The database accounts for 70% of all cases where mine rescue teams were still able to go underground.

Within this thesis this real distance to overcome for the rescuers is defined as “entrapment distance”. If no access to the underground is available, the entrapment distance is usually equal to the actual depth of the entrapment. With access available, it is decreased to the minimum of depth and the real distance the mine rescuers must overcome: For instance, if a mine rescue team makes the decision to horizontally re-drive 30 m of collapsed drift instead of drilling a vertical (surface to entrapment) depth of 100 m, the entrapment distance within the database is recorded as 30 m.

Correspondingly, Figure 13 plots the total duration of the rescue mission (in days) against the real entrapment distance (in meters). Each blue marker represents one case where such data is available. In addition, a trend line has been created using a second-degree polynomial (see grey box). Here, in contrast to Figure 12, a clearer relation between geological distances
and rescue time can be found. However, most of the cases remain without clear trend in the rectangle of 10 days and 500 m (bottom left of the diagram). Chile 2010 is again record-setting in the top right part of the diagram.

As stated above, such quantitative analyses are important measures to predict the scope of future incidents. Regarding the overall challenge of increasing depth in underground mining, Figure 13’s polynomial calculates half a year of rescue time for a “Chile” scenario occurring in 1500 m and even one year of total duration for a comparable rescue out of 2000 m depth. However, the following assessments will show that there is not such a trivial correlation for very unique large-scale mine rescue missions.

Besides accessibility, the scenario (rockfall vs. inundation) is another important individual parameter which influences the total duration of a mine rescue mission. Combining the aforementioned parameters, different groups of total duration have been calculated in separate columns of the database. They are represented in the first column of the subsequent Table 8.

<table>
<thead>
<tr>
<th>Group</th>
<th>Average rate [d/m]</th>
<th># Ref.</th>
<th>Variance</th>
<th>1500 m [d]</th>
<th>2000 m [d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD</td>
<td>0.07</td>
<td>24</td>
<td>0.0084</td>
<td>105</td>
<td>140</td>
</tr>
<tr>
<td>DE</td>
<td>0.23</td>
<td>23</td>
<td>0.1967</td>
<td>345</td>
<td>460</td>
</tr>
<tr>
<td>DD R-nA</td>
<td>0.03</td>
<td>9</td>
<td>0.0006</td>
<td>45</td>
<td>60</td>
</tr>
<tr>
<td>DD R-Acc</td>
<td>0.09</td>
<td>4</td>
<td>0.0021</td>
<td>135</td>
<td>180</td>
</tr>
<tr>
<td>DD I-nA</td>
<td>0.12</td>
<td>5</td>
<td>0.0223</td>
<td>180</td>
<td>240</td>
</tr>
<tr>
<td>DD I-Acc</td>
<td>0.11</td>
<td>6</td>
<td>0.0056</td>
<td>165</td>
<td>220</td>
</tr>
<tr>
<td>DE R-nA</td>
<td>0.35</td>
<td>9</td>
<td>0.4267</td>
<td>525</td>
<td>700</td>
</tr>
<tr>
<td>DE R-Acc</td>
<td>0.27</td>
<td>4</td>
<td>0.0767</td>
<td>495</td>
<td>540</td>
</tr>
<tr>
<td>DE I-nA</td>
<td>0.07</td>
<td>5</td>
<td>0.0012</td>
<td>105</td>
<td>140</td>
</tr>
<tr>
<td>DE I-Acc</td>
<td>0.11</td>
<td>6</td>
<td>0.0056</td>
<td>165</td>
<td>220</td>
</tr>
</tbody>
</table>

The second column of Table 8 shows the equivalent average progress rates in days per meter of depth respectively entrapment distance for each group. The last two columns extrapolate the average rates to great depths. However, many of the calculated figures rely on

17 “DD” stands for calculated durations based on the actual depth whereas “DE” durations are based on entrapment distances. “R” and “I” stand again for the two major scenarios of rockfall and inundation. The annex “Acc” shows the availability of access to the underground and “nA” respectively no access.
sparse data for the specific scenarios. As a result, values with five or less references (here: 4 and 5) or with statistical variances higher than 0.01 have been removed (see the two central columns and their cancelations). Rockfall scenarios seem to be highly individual and cannot be reliably extrapolated. The inundation scenarios show clearer trends that again indicate potentially long-lasting missions of several months when projected to great depths.

Another critical parameter for survival underground is the availability of fresh air to the trapped miners. Like existing access to the underground, the availability of fresh air is one more set of binary data in the database. Its evaluation shows that fresh air flow was available in 50% of the cases.

A further analysis visualized in Figure 14 shows no dependence of fresh air flow (FA) to any underground access (Acc). There is even one case (Lengede (11for14)) where fresh air reached the trapped miners through broken rock in the goaf whereas rescue teams had no access to reach them from underground.

Looking again on Table 8 (p. 39), major rockfall incidents with no access to the underground are the most frequently recorded events in the database (9 references shown for “R-nA”). Being forced to start the rescue mission on surface, their duration strongly relies on the achieved drilling times. The quantitative analysis of the separate drilling database gives an

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18 The first binary data calculated in this chapter was the information on EU membership of cases in Figure 11.
average drilling rate\textsuperscript{19} of 7.3 m/h for small diameter and 2.6 m/h for large diameter drill holes in past rescue missions:

<table>
<thead>
<tr>
<th><strong>Drill Type</strong></th>
<th><strong>Diameters [mm]</strong></th>
<th><strong>Average rate [m/h]</strong></th>
<th><strong>Extrapolated Duration for 1500 m [d]</strong></th>
<th><strong>Extrapolated Duration for 2000 m [d]</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot</td>
<td>&lt; 200 mm</td>
<td>7.3</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Rescue</td>
<td>&gt; 400 mm</td>
<td>2.6</td>
<td>25</td>
<td>33</td>
</tr>
</tbody>
</table>

Table 9 also shows the extrapolation of the average drilling rates to great depths: The sequence of pilot and rescue drilling add up to more than a month of drilling operation. This is a very different time frame compared to extrapolation of Figure 13 (see p. 38) which comes to half a year and respectively one year for the duration of a rescue mission.

Another vast time frame of the total rescue mission has to be taken into account to first locate the trapped miners. The subsequent Figure 15 shows that the most frequent location method was again (small diameter) drilling. Acoustic methods like hearing the trapped miners shouting (“Voice”) or tapping on steel pipes are, of course, limited to small entrapment distances.

The figure above is an example for quantitative analysis of qualitative data. Statistically evaluating the quantity of all cases is also pertinent while looking back on more general information: Figure 16 tells that nearly every second case was caused by a major rockfall delays.

\textsuperscript{19} Within this thesis, the term “drilling rate” is referring to gross drilling times including preparation, stops, and delays.
event. The second most common scenario is inundation. Thus, the prior scenario definition of chapter 2 can be confirmed by the database of past major mine rescue missions.

![Figure 16: Scenario Distribution](image)

Furthermore, inundation and rockfall represent two examples of event isomorphism. In his disaster research, Toft (1992) distinguishes four ways of organizational isomorphism:

- **Event isomorphism**, as same hazardous situations (e.g. a flooded mine) can cause different and independent incidents (here: individual cases).

- **Cross-organizational isomorphism**, when different companies belonging to the same industry have pointed comparable incidents.

- **Common mode isomorphism**, as organizations of different sectors possibly still work with comparable tools or procedures.

- **Self isomorphism**, when sub-units of large companies face comparable failures.

![Figure 17: Represented Commodities](image)
Figure 17 shows the distribution of commodities over all cases. Since this thesis compares and learns from both coal and hard rock mining, it applies *common mode isomorphism*. Although mining technology is frequently different\(^\text{20}\), the rescue missions and challenges are highly comparable, especially because mine fires play a less important role in the scope of this thesis.

Having a look at the affected mining companies (as owners or operators) of all incidents, it turns out that there is no case of *self isomorphism*. In other words, no mining company faced a long-lasting mine rescue mission two times, so far. Thus, the different scenarios considered in this assessment of the mining industry are subject to *cross-organizational isomorphism*. “The advantage of explicitly recognizing where organizational isomorphism does exist is that this recognition allows the learning process to be considerably speeded up.” (Toft 1992, p. 56)

The previous quantitative analysis has proven the relevance of this thesis’ research in the field of long-lasting entrapments. The extrapolation of the available data helps to predict the dimension of a corresponding scenario at great depths: To rescue miners trapped at great depths with no access for rescue teams to go underground would take at least several months. This fact leads to the demand for a mine rescue management concept which is again subject to this thesis.

Although statistical evaluation leads to important validation processes, the single figures change considerably from case to case. One has to think of highly individual cases. This property justifies detailed, qualitative case studies which are following in chapter 4. Still, the identified isomorphism of the cases motivates general learning from individual strategies and success stories.

\(^{20}\) Cutting technology is common in coal mining whereas drill and blast operations are established in hard rock mines.
4 Case Studies of Selected Reference Mine Rescue Missions

After the quantitative analysis of the database in the last chapter, detailed qualitative case studies on six selected mine rescue missions follow in chapter 4. Chapter 4.1 introduces the methodology of case study research and qualitative methods – mainly following the principles of Yin and Creswell. The coding procedure, based on Hahn, then provides a procedure for the six single case studies in chapter 4.2.

The major mine rescue missions of San José, Wangjialing, Beaconsfield, Quecreek, Lassing and Lengede are individually described and analyzed. Here, the thesis provides a compilation of separate, independent sources and views. These comprehensive single case studies are then subject to multiple case studies in chapter 4.3. The synthesis of single case facts leads to qualitative lessons learned which are valuable sources for the thesis’ mine rescue management concept to support future missions.

4.1 Methodology of Qualitative Case Study Research

This chapter introduces (single and multiple) case study research and qualitative research (especially mixed methods and coding) as the primary methods for the subsequent part of the thesis.

Case study research is a scientific method which originates from social sciences. Today, it is widely applied in psychology, medicine, law and political sciences (Creswell 2013). Yin (2014) defines that case studies examine contemporary phenomena by careful and elaborate data collection procedures (see 3.2). They can put into focus a single case or multiple cases (Creswell 2013).

A case needs certain boundaries “such as a specific place and time” (Creswell 2013, p. 98), which applies to the defined mine rescue missions of which some will be analyzed as single cases. The final case study comprises a description and an analysis dedicated to certain aspects. Specific lessons or theories can be the outcome of case study research. (Creswell 2013)
Yin names, besides others, surveys and statistical modeling as alternatives to case study research. They are applied in this thesis as well – like the international survey on major hazards in mining (see 2.1) and the statistical evaluation of the compiled mine rescue database in chapter 3.5. In contrast, the subsequent detailed analysis of selected major mine rescue missions “will have more variables of interest than data points” (Yin 2014, p. 2).

Although past mine rescue missions cannot be considered as “contemporary”, they correspond to Yin’s further selection criteria:

- The researcher is questioning “how” and “why” and
- The researcher cannot control the studied events.

Some scientists see case studies only as the object being studied but not as a methodology. But this thesis, following the philosophy of Yin (2014) and Creswell (2013), not only analyzes cases; comprehensive cases are also the product of this study. Diverse data collection and qualitative analysis lead to a unique view on selected mine rescue missions and enable systematic learning with focus on mine rescue management.

The high amount of qualitative data and the high degree of individuality of each rescue mission are the primary reasons to apply case study research in this thesis. The socio-scientific approach of evaluating systems, procedures or incidents is going to provide interesting conclusions for this specific field of mining engineering.

Having chosen the method of case study research, the subsequent step is to design the study (Yin 2014). After a broad quantitative analysis in chapter 3.5, the subsequent chapter 4.2 provides six qualitative single case studies. Finally, a multiple case study analysis (see 4.3) puts together and compares the single case results. Systematically combining quantitative and qualitative analyses is a relatively new approach and has recently been defined as “mixed methods research” by Creswell (2014):

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21 Following the cross-case analysis approach of Miles et al. (2014), the quantitative analysis in chapter 3.5 is variable-oriented. It covers more than fifty cases and puts into focus common variables rather than case details. It is good for identifying overall relationships, benchmarks and trends. The subsequent multiple case study analysis is, on the other hand, case-oriented. Case-oriented studies are dedicated to single sets and causes and only compare a small number of cases. That helps to identify specific patterns. Miles et al. recommend combining the two approaches and so does this thesis.
Referring to Creswell, this thesis applies “explanatory sequential mixed methods”. Prior quantitative results are qualitatively explained by a follow-up qualitative approach. For example, we are interested in understanding how the identified record of Chile 2010 could have been survived and successfully managed. Thus, especially the subsequent case selection is based on the statistical evaluation of quantitative data. Furthermore, the validity of the qualitatively generated theory can be assessed by looking back on the quantitative conclusions.

With respect to case studies, data collection is the first major step of single case study research. The corresponding approach for this thesis and its database has already been described in the previous chapters. Then, the real analysis takes place. There is no fixed procedure for the analysis. Displaying data in different ways and the identification of patterns are general strategies. (Yin 2014) The strategy for this thesis is to do qualitative analysis.

“Qualitative research is research that involves analyzing and interpreting texts [...] in order to discover meaningful patterns descriptive of a particular phenomenon.” (Auerbach and Silverstein 2003, p. 3)

Creswell (2014) gives properties of qualitative research which this thesis fulfills: The researcher is the key instrument collecting multiple sources of data. He (or she) identifies certain themes which influence the emerging design of the study. Finally, the variety of themes identified in the analysis creates a holistic model of the studied phenomena. Stake (2010) defines this last step as synthesis (“putting things together”) as opposed to analysis which takes things apart.

As for case study research, data collection is also a major step in qualitative research. The related organization of data plays a central role which has been described in chapter 3.4 (see Figure 10, p. 35). The MS Word transcript of identified cases puts together relevant text passages of the related text sources. They have been identified during the reading process. When copied to the transcript, each passage has been given a memo that summarizes the specific content or statement of the text passage. The heading level function of MS Word puts all memos (and their text passage) in a hierarchical order.

“Writing notes or memos in the margins of field notes or transcripts or under photographs helps in this initial process of exploring a database.” (Creswell 2013, p. 183) The researcher’s
memos constitute the link between data collection and analysis. Memos are intuitively written. Correspondingly, this step is also called open or inductive coding. (Patton 2009) Coding, as the primary qualitative method of qualitative analysis in this thesis, will be specified below.

In order to keep this vast amount of data manageable, the transcripts for the selected single cases are moved to individual “case records”. These records still contain all information, since it will be used for the case study analysis itself. But its organization is more advanced than in the transcript of raw data. (Patton 2009) Taking advantage of its sorting and filtering functions, MS Excel has been chosen to build up the case records and to do the further coding for this thesis.

**Coding** is “reducing the data into meaningful segments and assigning names for the segments” (Creswell 2013, p. 180). Conducting different steps or spirals of coding creates a few key themes out of a broad raw (text) data basis. Hahn (2008) defines these steps as levels which leads to the following systematic coding approach, as illustrated in Figure 18:

![Figure 18: Coding (based on Hahn (2008))](image)

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22 “The human mind finds patterns almost intuitively; it needs no how-to advice. But patterns don’t just happen; we construct them from our observations of reoccurring phenomena. The important thing is to be able to (a) see added evidence of the same pattern and (b) remain open to disconfirming evidence when it appears.” (Miles et al. 2014, p. 278)
The thesis’s coding procedure follows Hahn’s procedure. All afore mentioned memos (all headings and sub-headings in the MS Word transcript) become Level 1 Codes. Moving them to the MS Excel case record already prepares the Level 2 Coding. Level 2 Coding is still done intuitively but not over such a long time span as in the data collection procedure, when the memos (Level 1 codes) were created. Doing Level 2 Coding for all relevant cases in a row helped to harmonize the codes. Also Excel’s word recognition and an afterwards cross-check through Excel’s sorting functions help to carefully standardize the codes.

Then, Level 3 Coding was conducted on a cross-case level. A table (see Appendix 1, p. 163) showing all Level 2 codes of each case helped to see patterns and to define summarizing and combining Level 3 codes. These Level 3 codes were then applied to each case. Again, a table (see Appendix 2) of the Level 3 codes’ distribution over the cases helped to prepare the final Level 4 Coding. The resulting Level 4 codes are already clearly putting into focus the management-related purpose of the full study.

This way of grouping data is a key principle of qualitative research. The most general themes (here Level 4 codes) as an outcome of the coding are the basis for the final interpretation (or synthesis) phase. In contrast to single pieces of data, they have a higher meaning which can – on the one hand – be verified in different cases and – on the other hand – be generalized to theory building. Within this thesis, this will be the incorporation of lessons learned into the developed mine rescue management concept.

4.2 Single Case Study Analyses

The selection of cases for the following single case studies is based on results of the quantitative analysis in chapter 3.5. Certain records or benchmarks made specific cases candidates for conducting a full analysis. Table 10 shows the six cases in chronological order that are subject to single case studies in the subsequent sub-chapters (see left column). Besides salt, all major groups of commodities are represented and, besides Africa, all continents can be found in the list. Rationale and motivation for each selection is given below for each single

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23 The careful citation procedures (see 3.4) are kept in this database as well. Still, each cell or piece of information is referenced.
case. Furthermore, this chapter introduces the procedure for the following case studies and anticipates more details of the cross-case coding procedure.

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Mine</th>
<th>Country</th>
<th>Year</th>
<th>Commodity</th>
<th>Scenario</th>
<th>Duration Total [d]</th>
<th>No. of Survivors</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2.1</td>
<td>San José</td>
<td>Chile</td>
<td>2010</td>
<td>Copper</td>
<td>R</td>
<td>69</td>
<td>33</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Wangjialing</td>
<td>China</td>
<td>2010</td>
<td>Coal</td>
<td>I</td>
<td>8</td>
<td>115</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Beaconsfield</td>
<td>Australia</td>
<td>2006</td>
<td>Gold</td>
<td>R</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Quecreek</td>
<td>U.S.</td>
<td>2002</td>
<td>Coal</td>
<td>I</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>4.2.5</td>
<td>Lassing</td>
<td>Austria</td>
<td>1998</td>
<td>Talc</td>
<td>I</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>4.2.6</td>
<td>Lengede</td>
<td>Germany</td>
<td>1963</td>
<td>Iron Ore</td>
<td>I</td>
<td>14</td>
<td>11+3</td>
</tr>
</tbody>
</table>

Chile’s **San José** copper-gold mine collapsed in 2010. 33 miners were trapped for a record duration of 69 days. As already shown in chapters 3.3 and 3.5, it is maybe the most famous mine rescue mission in recent history. From the psychological perspective, it is interesting to study group phenomena which took place in a relatively large open void which extended over more than 1,000 m of drifts. With respect to technology, San José shows the highest entrapment distance of 700 m (here equal to the depth; see 3.5) and a considerably high number of 13 drilling operations in total. The thesis’ case record for this rescue mission contains 184 text passages.

Referring to Table 6 (p. 31), China faced the highest (national) amount of major mine rescue missions in the scope of this thesis. The inundation of the **Wangjialing** coal mine represents a recent mission with relatively high availability of data. Furthermore, the 115 survivors are the second-highest number of rescued miners within the database. 52 text passages out of the case record are subject to the Wangjialing case study.

**Beaconsfield** 2006 is the only case identified in the mining country of Australia. Two miners were trapped at considerable depth (925 m) and duration (14 days). They survived in collapsed rock thanks to a small telehandler, in which they could hardly move. The case record for this mission is relatively small (38 text passages).

As already mentioned in chapter 3.3, **Quecreek** 2002 is the last U.S. incident fitting the scope of this thesis. Furthermore, it is an extreme case because there was no supply of fresh air to
the trapped miners which finally just had an open void of about 90 m³. Quecreek represents one of only four room-and-pillar cases in the database. A high number of drills (13 in total) were part of the rescue mission in this flooded coal mine. The thesis’ case record for this rescue mission puts together 228 text passages.

**Lassing**, Austria 1998, is one out of ten single entrapments. One miner survived for 9.5 days without external support. Nevertheless, Lassing, as the second last incident in Europe, globally stands for an example of unsatisfactory mine rescue management (Alexander et al. 2010; Everly, Jr. et al. 2008; Hersche and Wenker 1999). Altogether 161 text passages out of the case record are going to be analyzed in the subsequent case study.

The **Lengede** iron ore mine flooded in 1963. Besides other survivors, two different groups of miners were trapped for 8 and 14 days. For the purpose of the single case study, they are compiled again. Lengede as a case is interesting because the two groups of trapped miners were rescued independently and under different conditions. Both approaches set standards for subsequent comparable incidents in the world. Although it is the oldest case in this study, the Lengede case record is by far the longest with 382 text passages to be analyzed in the following.

Qualitative research and its method of case study analysis need to put into focus specific research questions. As told before, they are usually “how” and “why” questions. The first question of the subsequent studies is, “Why were certain mine rescue missions successful?”. The answers or lessons lead to the question of implementation to mine rescue management: “How can one prepare for a scenario that is unforeseen?”

With respect to these research questions, the single case studies are structured in the following way: Each case study is introduced by a description of the incident together with a drawing which puts together the cause of the incident, the location of the trapped miners and the rescue strategies. The second part of the case study is analysis. Here, coding provides a frame to systematically generate and organize results or lessons to learn. Here, the final Level 4 codes can also be seen as research sub-questions.
The general coding approach of this thesis has already been described at the end of chapter 4.1. Since it has been done on a cross-case scale, its description here anticipates parts of the multiple case study analysis in chapter 4.3. Procedure and code definitions of the coding procedure are documented in Appendices 1 and 2. Following the general introduction of the previous chapter, some more detailed issues of the coding are discussed here:

There were different judgmental Level 2 codes24 like “lagging” or “accelerating” factors, “problems”, “mistakes” or “luck” and “evaluation”. In Level 3, they were all re-assigned, e.g. to technical or organizational codes. For the Level 2 codes of “behavior”, “nutrition” and “psychology”, it was important to differ between the situation of the trapped miners before and after the establishment of external supply (e.g. through a pilot drill hole). Everything before such supply by mine rescue teams is coded in Level 3 as “survival” and everything afterwards is coded as “support”.

Also the Level 2 codes of “information” and “communication” were inaccurate. With respect to the considered internal or external receiver, they were assigned to the Level 3 codes “stakeholder” (like communication to media and families), “delegation” (information of different rescue teams or duties) and “support” (when the trapped miners themselves were contacted). Accordingly, also the Level 2 code “management” was decomposed because it is the final point of interest or the overall sum of all codes and not a single one.

Altogether, the coding causes nine resulting Level 4 codes. However “case description” is just used to introduce each case study wherever the other eight codes are possible components to the developed mine rescue management concept. Each code is assigned to a symbol that will facilitate rediscovering each code in the single case studies. The Level 4 codes and symbols are shortly explained in alphabetical order below:

**Case Description** starts with the introduction of general mine information and the cause of the incident. The further description comprises information like the location of the trapped miners, the rescue strategy and the sequence of the related steps of the rescue mission.

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24 All Level 2 codes that are assigned „none“ in the Level 3 column of Appendix 1, have been re-assigned to other Level 3 codes, which is explained here.
Delegation of responsibilities, here symbolized by a small organigram, is an important aspect of managing mine rescue missions. Besides defined roles and information flow, also leadership as such is of interest.

External Aid is defined as support to the mine rescue teams and managers of the affected mine and company. That could be from external experts like psychologists or mutual aid from neighboring mines and international aid in general. A different important group offering external aid is public authorities like mining authorities, police, firefighters and the army.

Logistics is another important aspect of mine rescue missions. Heavy equipment has to be transported to the site. In addition, rescue teams and other stakeholders need certain infrastructure, especially when it comes to long-lasting missions.

Natural Events comprises the handling of (partly unexpected) natural influences on the mine rescue mission. This can be the mastering of rock mechanics like preventing secondary roof collapses or maintaining the overpressure of an air pocket (see p. 15). Also dewatering of flooded parts of the mine is assigned to this code.\(^{25}\)

Preventive Measures comprise both the effect of actually installed preventive measures like refuge chambers but also learnings for possible future installations. Especially the previously given “Survival” aspects could be implemented in next-generation refuge chambers or safety trainings.

Stakeholders of a major mine rescue mission need to be managed as well. Especially families of the trapped miners and international media require continuous information flow. But also neighbors of the mine can be effected, e.g. by unstable rock conditions or for the access of drilling equipment.

\(^{25}\)Dewatering (or drainage) could have been coded as “Technology” as well. But the handling of geological circumstances like rock behavior and water inflow is an interesting parallel of mine rescue to mining engineering in general.
The **Support** of Trapped miners comprises physical support like nutrition and first aid as well as psychological aid by means of family communication or material for passing the time and for distraction. Especially small-diameter drill holes can enable such support to those trapped.

**Technology** is necessary for a successful rescue of miners trapped underground. Depending on the circumstances, tracking the miners is the first large technological issue. Then, for most missions, drilling small pilot and large rescue drill holes is one more integral part of mine rescue.

The explanation of the Level 4 codes above has been prepared using their subordinate Level 2 and Level 3 codes. Here again, the sorting and filtering functions of MS Excel permit a quick overview and accurate data handling within the case record. It becomes obvious that these Level 4 codes are important aspects of mine rescue management. Together with their dissection above, the coding procedure has already provided some valuable qualitative analysis for the multiple case study which follows in chapter 4.3.

For the subsequent step, the Level 4 codes and symbols structure each of the single case studies and respectively provide systematic learning for all of the already identified aspects of mine rescue management. As announced in the previous Table 10 (see p. 50), each single case study can be found in a separate sub-chapter. Whenever triangulation was not available to a single piece of information, it is referenced individually.

### 4.2.1 San José, Chile 2010

The San José copper-gold mine of the San Esteban Mining Company is near Copiapó in Chile’s Atacama region. The vein type deposit was mined in a sublevel stoping operation (Fiscor 2010). Access was achieved by a decline and a small-diameter ventilation shaft completed the airflow circuit. On Thursday, August 5th 2010 the decline collapsed. This major rockfall was a result of weakened barrier pillars between an only partly backfilled stope and the decline.
Miners who were working above the rockfall were able to escape immediately. 33 miners who were working below the 135 m high collapse zone became trapped underground. They tried to escape through the ventilation shaft. But the miners could not find one ladder because the mining company did not maintain this second means of escape as it was required to do.

First rescue efforts were conducted by local miners and regional mine rescue teams because San José did not have own first response capabilities. They tried to get access through the open part of the decline and through the ventilation shaft. Both openings showed partial blockages by rockfall. On August 7th, two days after the initial rockfall, a second collapse destroyed the ventilation shaft and also made access to the decline too dangerous. Thus, the depth of 700 m of the trapped miners has the same value as the real entrapment distance of the following rescue mission.

Since mine rescue teams had no more chance to go underground after the second collapse, surface drilling became the main26 search and rescue strategy at San José. There was no sign of life but hope that the lowest parts of the mine had sustained the collapses. Several small diameter drills failed to hit mine openings around the crucial 700 m level. But in the morning of August 22nd, a reverse-circulation hammer drill reached a void at a depth of 688 m. First tapping, and second a message attached to the drilling steel proved that all 33 miners were alive.

The trapped miners had survived 17 days without external support. They had access to a permanent refuge chamber where they found some emergency supplies of food and water. In addition, more than 1 km of drifts was still open which let the 33 some walking for personal distance, exercising and to relieve themselves. Extreme rationing extended the supplies from three to 17 days: Every 48 hours each man received two spoonfuls of tuna, a sip of milk and one biscuit. When water ran out, they drank from mining machinery radiators and mine water. The miners also used the machinery’s batteries to charge their cap lamps.

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26 A second try to reopen the ventilation shaft failed on August 19th, increasing cracks because of rock pressure made a further rescue work underground too dangerous and futile.
Group dynamics underground led to different roles and leadership: Shift foreman Luis Urzúa was the formal leader of the group whereas others became religious preachers and subsequently (after the supply drills) communication specialist and medic. However, important decisions were made in daily democratic assemblies. Playing cards or domino was some entertainment in the first 17 days without contact to surface. Further group dynamics broke the 33 into three groups who slept in different parts of the remaining mine openings: the refuge, the ramp, and the workshop.

Altogether 10 small-diameter drills were made parallel. This strategy of redundancy was chosen because of the life-critical factor of time to find and supply the trapped miners. On August 23rd, one day after the first successful breakthrough, two more small-diameter drills reached the trapped miners. One reached the refuge chamber (as the first did) and one reached the workshop.

The small-diameter drills connecting the underground with the surface were used to support the trapped miners. The first metal cylinders sent to the trapped miners contained rehydration tablets and glucose gels. In the first 17 days, the miners had lost about 9 kg of body weight each. In the following, one hole was reserved for the (discontinuous) supply of nutrition and equipment. The second one contained pipes and cables for a continuous supply of water, power and information. The third one provided ventilation.

After having recovered, the trapped miners received regular food through the capsules. Medicine included vitamins and anti-depressants. Equipment comprised cap lamps, clothing, camp beds and a rolled-up TV. The small water pipe provided 3 liters of hot showering water and 1.5 liters of cold drinking water per miner and day. Fiber optic communication lines enabled medical monitoring, psychological counseling, and family conversation. The trapped miners also received trainings in exercising, first aid, and media.

After having found the trapped miners alive, planning for the rescue of the 33 started immediately. Again, the rescue managers chose the strategy of redundancy: three parallel large-diameter rescue drillings applying different technologies were set into operation and named Plan A, B and C:
The Plan A Strata 950 raise-bore machine of Codelco’s Andina mine was originally made to drill ventilation shafts.

The Plan B Schramm T130XD drill, designed to drill water wells, should widen a previously drilled pilot drill hole into the workshop.

The Plan C RIG-422 from the oil industry was, in theory, the fastest but also most expensive of the three rigs and had a target depth of 597 m.

For Plan B, Geotec prepared one more pilot drill hole into the workshop. The Schramm 685 reverse air rig needed five days to drill 624 m (5.2 m/h) with a diameter of 140 mm. Then, the larger T130XD widened it in two passes to a final diameter of 600 mm (first pass: 300 mm) using a down-the-hole (DTH) hammer. Cuttings fall through the pilot drill hole and had to be removed continuously by the trapped miners. The first 50 m through loose rock were cased. Afterwards solid granite was the predominant rock which was hard but stable. Drilling almost 1 m/h, Plan B became the successful rescue drill. Plan B reached the trapped miners on October 9th. At that time, Plan A had reached 598 m and Plan C 372 m.

Underground, the group stayed divided into three groups of eleven. 8 hour shifts guaranteed a continuous work supporting the rescue drill by removing cuttings of the Plan B drill and unloading the supply cylinders. While working, sleeping and relaxing separately, the whole group still met for meals, prayer sessions and meetings. External support and internal organization created a relatively usual life which was important to cope with the situation. Artificial lighting even caused a day-night rhythm.

In the morning of October 12th, the trapped miners were turned to a liquid diet and were told to wear waistbands in preparation of the ascending. In addition, they ate aspirin to prevent blood clotting. After test runs with the empty Fénix 2 capsule, two experienced rescue men were sent underground to support the escape of the 33. First, four of the fittest miners were brought to surface. Then, the least healthy miners followed. The originally scheduled hour per ride was soon decreased two 25 minutes. In the evening of October 13th, the last miner left the mine.

While ascending, each miner wore a NASA bio-harness to monitor health status and a spandex suit. Furthermore, they were wearing sunglasses to protect the eyes after 69 days without sunlight. The Fénix 2 capsule itself was designed by NASA as well. This capsule followed the idea of the Dahlbusch bomb (see p. 30). In addition,
it contained three bottles of compressed air, a communication system and an emergency escape hatch which would have allowed the miner to travel back underground in case the capsule got stuck. To prevent loosing track in intersections with other boreholes, the capsule was about 4 m long at a diameter of 53 cm. Also shock-absorbing wheels were installed at the outside for a smooth ride.

The total cost of the rescue mission was 20 to 25 million US Dollars. More than 18 million dollars came from the Chilean government. A lot of mutual aid was donated by different companies involved. The San Esteban mining company itself went bankrupt.† The subsequent Figure 19 visualizes the previously described rescue drillings to the 33 miners trapped underground:

![Figure 19: San José Rescue – side view, not to scale](image)

On surface, the Chilean government soon overtook the management of the approaching major mine rescue mission. Approved by decree and on behalf of President Pinera, Chile’s mining minister Laurence Golborne became the leader of the

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† It was removed from the rescue management at an early stage by government. In addition, their assets had been frozen.
San José rescue. René Aguilar, head of safety from Codelco’s El Teniente mine, became deputy chief and André Sougarret, manager of El Teniente, became the chief engineer of the rescue. While Sougarret was responsible for the drilling operations, Aguilar, with his background in psychology, established relations to the miners’ families.

This small leader-team managed the search and rescue operation at San José. Golborne did not make decisions on his own but asked decisive questions to the small team of mining engineering experts. He did not have background in mining but in management of projects and leading of teams (Jordán et al. 2011). This shape of organization was crucial to accelerate decisions and cooperation because reaching the miners trapped without supply from surface so far, was time-critical. Rescuing the miners as the target goal was an engineering task. Thus, experts from the mining industry made his inner management circle.

However, besides the inner rescue mission, more management tasks regarding different stakeholders evolved in the following days and weeks: Up to 2,000 journalists reported from the site. Near the mine, the trapped miners’ families assembled a tent-village. The number of relatives temporarily living in the desert peaked to more than 2,000. Even a school for the children has been established. When telephone connections were available to the trapped miners, psychologists supported the families in preparation of individual conversations.

Besides the mining minister Golborne, there was more inclusion of politicians to the mine rescue. To support the rescue leaders, Christián Barra, a representative of the Ministry of Interior, fostered relations to the families of the trapped miners. He also managed the interaction between Golborne and the government. President Pinera guaranteed political and financial support during all phases of the mission.

The technical realization of the rescue strategy was fully based on external aid. Drilling equipment and experts of Chile’s state-owned mining company Codelco has already been mentioned above. Furthermore, large international cooperation was started. Drilling experts from the U.S. helped to realize the successful rescue drill Plan B while South African and Canadian know-how was used in the alternatives A and C. Altogether, 20 different companies were working on site during the rescue mission.
Medical and psychological know-how has been provided by NASA. German mine rescue experts, contacted by the Chilean Chamber of Commerce, shared lessons learned in the Lengede rescue (see 4.2.6) and established contact to the International Mines Rescue Body (IMRB; see p. 5) which caused further aid from international mine rescue experts. More international aid was provided by means of special drilling tools, communication technology, and logistics.

Due to the vast amount of external support, logistics was one more crucial field of this longest-lasting rescue mission. Most of the equipment coming from the U.S. was shipped by UPS at no charge. And even Plan B’s drill rig had to be transported more than 1,000 km from a different Chilean mine. Chile’s Army organized the supply chain from harbors and airports through the desert to the rescuers and families at the San José mine.

The case of San José covers all Level 4 codes that are relevant to this thesis. Besides the records identified during the quantitative analysis, this qualitative analysis proves this successful rescue mission to be of unique complexity to learn from.

4.2.2 Wangjialing, China 2010

The Wangjialing coal mine is in China’s Shanxi province. The mine is state-owned and operated by the Huajin Coking Coal Corporation. (Sun Yuejin 2011) On Sunday, March 28th 2010 – the coal mine was still under construction – mine workers accidently cut into an old, water-filled shaft. Violation of safety standards and policies regarding water leakage prevention caused a major water-inflow. Of 261 people underground, 108 could instantly leave the mine, while 153 miners became trapped by the inundation.

There were no signs of survival until April 2nd when rescue teams heard tapping on metal pipes underground. It took three more days to pump out more murky water to allow mine rescue divers to reach the first group of nine miners trapped underground. Another 11 hours later, on Monday April 5th, altogether 115 miners were rescued after being trapped underground for eight days. Having spent 179 hours in mine water, the trapped miners were
carried out of the mine. They were in weak condition because of dehydration and hypothermia but all recovered soon in hospital.

After the initial incident, the mine openings were still accessible for the mine rescue teams. Their primary strategy to rescue the trapped miners was to pump and drain the water. All pumps, pipes, transformers and cables had to be transported by mine rescue workers through a 600 m long and 25° dipping decline. (Sun Yuejin 2011) In addition, the Wangjialing coal mine poses the risk of high methane concentrations which hampered the rescue operations at a larger distance.

Specially approved divers were sent underground to search for trapped miners and to assess the further conditions of the mine. Poor visibility because of the murky water was one more natural constraint to the mine rescue work. Nevertheless, on April 4th a diver saw reflections of a moving cap lamp in the water which led to the location of a group of trapped miners.

On surface, a previously developed emergency response plan came into operation and a command center was set up on the same day when the inundation occurred. This plan can be seen as a preventive measure that supported the progress of the rescue mission. However, no preventive measures such as emergency supplies underground were available to help the trapped miners directly:

The miners had been trapped in separate groups at different locations of the mine. Some attached their belts on remaining mine infrastructure to prevent drowning during sleep while others sat in floating mine carts. To keep battery power, the groups only occasionally turned on their cap lamps. Some ate coal, timber, paper or cotton and drank mine water28 and urine to stay alive.

The largest group of miners was reached by a supply drill after five days. Nutrition by 560 glucose solutions supported their survival. A second small-diameter drill was put to create a drainage channel from a shaft to unused drifts of the mine. The prior assembly of necessary drainage and drilling equipment was complicated by the remote location of the mine.

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28 Some softened the tree bark by dipping it in mine water and others could use a plastic bottle to clear the mine water by settling suspended particles before drinking it.
Statements regarding the total number of rescuers vary between 1,500 and 5,800 mine rescue men. More than 200 media representatives reported on site. Furthermore, a Vice Premier of China went to site already at the first night and partly directed the operations. (Sun Yuejin 2011)

The available information does not allow for an accurate drawing of the mine rescue mission. Also the Level 4 codes of delegation, external aid, logistics, and the support of the trapped miners are not mentioned explicitly. Technical aid came from other Chinese mines and authorities. As stated above, some trapped miners received external support (glucose) five days after the incident.

4.2.3 Beaconsfield, Australia 2006

The Beaconsfield gold mine is in Northern Tasmania, Australia. On Tuesday, April 25th 2006, a hangingwall shear slipped and caused a seismic event. Two miners, Todd Russell and Brant Webb, became trapped under collapsed roof in their telehandler basket. The operator Larry Knight, standing behind the machine at that moment, was killed immediately by rockfall. (Melick 2007)

In total, the two miners were trapped for 14 days until their final rescue on Tuesday, May 9th. The basket withstood the rock pressure and protected a small void 925 m below surface. Within that void, the miners had to lie next to each other; they were not able to sit or stand. They had access to fresh air flow which was warm but still bared the risk of hypothermia because of their wet cloths.

There were no preventive measures that supported the trapped miners.29 To survive, they collected mine water and urine with their helmets which was the only nutrition for the first six days. They sang songs and told stories for cheering up and snuggled against each other to bear the cold.

Finding the trapped miners’ exact location took five days. The tracking technology applied was a thermal imaging camera. This was applicable because the mine

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29 However, the re-enforced telehandler cage protected the miners’ lives, as mentioned above.
rescue teams still had access to go underground via the mine’s ramp. One day later, a 90-mm-diameter pipe connection was established through the collapsed rock to the miners. The pipe was then used for communication and supply.

To physically support the trapped miners, food, water, deodorants, blankets, light, music and reading material was sent through the pipe. Besides such supplies, the communication through the pipe was an important psychological support. Contact to the families by letters was crucial to the miners’ mental well-being since they got the support pipe. Knowing that a well-known expert (Peter Hatswell) would lead the rescue and being able to speak to him strengthened the trapped miners’ moral as well.

The first rescue approach was to simply dig out the trapped miners. But unstable rock conditions made this strategy too dangerous. Thus, preventing major vibration (e.g. by percussion drills) was crucial to prevent more rockfall or even a major second collapse. Thus, the final rescue strategy was to drive an escape tunnel through the solid rock between the main ramp and the entrapment. Low-impact explosives and hand tools helped to establish this means of escape 14 days after the initial event. The trapped miners supported this rescue mission by moving rock, cutting pipes and examining ground. The subsequent Figure 20 summarizes the location of the rapped miners and the rescue strategy:

![Figure 20: Beaconsfield Rescue – side view, not to scale](image-url)
The Level 4 codes of delegation, external aid, logistics and stakeholders are not represented in this study. Beaconsfield was mainly an Australian operation with support of the Australian mainland. As told above, Peter Hatswell led the mission and the families’ letters were important support to the trapped miners.

4.2.4 Quecreek, USA 2002

The Quecreek No. 1 mine is in Somerset County, Pennsylvania. The Black Wolf Coal Company mined hard coal since 2001 applying the room-and-pillar mining method. In the evening of Wednesday (9 p.m.), July 24th 2002, a continuous miner accidently broke through into the abandoned neighboring Harrison No. 2 mine. Plans of the Harrison No. 2 mine (formerly operated by the Saxman Coal and Coke Company) were inaccurate regarding the outline of the old mine workings. The Harrison No. 2 mine was flooded showing a water level which was more than 4 m above the four portals of the new Quecreek mine (Fiscor 2002).

Nine miners of Quecreek’s effected 1-Left section became trapped for more than three days in the quickly inundated mine. Nine miners from other sections of the mine were able to escape. They had been warned over the mine’s radio system by the 1-Left crew. Soon after that warning they lost contact. The 1-Left section’s escape-way was already impassable because of the increasing water level and nine miners had to retreat to their workplace which was slightly dipping up.

Just a location of about 70 m² and 1.2 m height stayed above the water level. This point was more than 2 km away from the mine entrance at a depth of 73 m. Having no access to go underground, the primary strategy of the mine rescue teams was to drill a rescue hole. Since the water kept rising, parallel pumping through drainage drill holes and at the mine portals was crucial as well.

One hour after the initial incident, a command center was established in the mine office near the portals on surface. Fast decisions were made by the company’s management which led to an early integration of external experts and a non-bureaucratic initiation of supply chains. Altogether 200 professionals were working on the rescue of the trapped miners.
Suppliers of applicable pumping and drilling equipment were contacted immediately. Other contractors were told to prepare possible drilling sites and to open dewatering accesses of the old Harrison No. 2 mine. The collar preparation in the bedrock by excavator and concrete could be completed before the drilling rigs arrived at the site.

Establishing a small-diameter supply drill hole to potential survivors in the 1-Left section was the first priority. The Bartels drilling company provided a suitable drill rig at midnight. Before starting drilling, the location of the drill was determined and confirmed by two independently acting surveying companies. The two had worked at Quecreek before. By Thursday, 2 a.m. both surveying companies had completed their measures, which combined surface GPS positioning and matching against plans of the underground mine.

The surface location was on open farm land which could be accessed and prepared quickly. Underground, the drill hole should be able to reach an intersection of the room-and-pillar system, 60 m away from the face. This point was chosen because it was the highest point of the flooded 1-Left section and last surveyed some days ago. Bartels started drilling at 2:50 a.m. on Thursday, 25th and reached the trapped miners on 5:06 a.m. The 165-mm down-the-hole (DTH) hammer drilled the 70 m entrapment distance at 31.3 m/h.

It was the sign of life and the approval of their location when the rescuers heard the trapped miners tapping on the drill steel. The miners hit the drill steel in a given manner: MSHA stickers in the hard hats told the trapped to hit three times showing survival and nine times giving the number of survivors. The specified answer from surface was a short lift, turn and lowering back of the drill steel. (Brady et al. 2003)

There were also MSHA stickers providing barricading instructions. However, the first choice of the 1-Left miners was evacuation. When they noticed that all escape-ways were blocked by water, they went back to the face which was the highest elevation of the section. On their way, they found three canisters of water and subsequently a lunch box and some cans of drinks which the nine miners shared during their entrapment.
At the face, they started to assemble barricades with concrete blocks and ventilation stoppings. Parts had to be reconstructed when the pilot drill arrived out of the initial barricade’s layout. Finally, the increasing water level forced the men to leave the drill hole as well as the incomplete barricade. They were exhausted, wet and cold. As a result, the trapped miners sat close to each other and a roof bolting machine that was still warm. (Brady et al. 2003)

First measures showed that the trapped miners’ ambient air contained only 17 percent of oxygen. The water seal had cut off supply of fresh air to the nine miners. Since they were already reporting breathing problems and energy loss, the small-diameter drill was used to insert compressed air, which increased the oxygen level to 19 percent. Furthermore, the air was heated to 37°C to prevent hypothermia during the entrapment.

However, the air injection made tele-communication impossible. Furthermore, a few hours later the trapped miners had to retreat from the drill hole because of the rising water. The air supply got sealed off by water. Shortly before Thursday noon, the last tapping was registered on surface as the last sign of life until Saturday night. MSHA’s seismic location system kept working but was disturbed by the noise of heavy rescue equipment. The decision was to keep the air compressors running to provide additional overpressure through the pilot drill hole in order to maintain the open void underground.

Some miners broke down after they had lost contact to the pilot drill hole. Psychological countermeasures were prayer sessions and hand-written notes that were put in plastic bottles to be found in potential recovery work. In preparation of their death, some towed up against each other to be found together while others made the decision to die alone. (Boyer 2002)

After the first small-diameter drill hole had proven that nine miners were alive underground and that the water level was still increasing, two parallel major rescue strategies were applied: A large-diameter rescue drill was started Thursday evening and several drainage holes were drilled into the mine’s lowest locations in the mains and the 1-Right section to establish parallel pumping.
On Friday 26th, two more pilot drill holes were drilled to search for miners that possibly have escaped into the old Harrison No. 2 mine. But one hit coal and the other did not show any signs of life. The subsequent Figure 21 provides an overview of the situation at the 1-Left Section of the Quecreek mine and the abandoned Harrison No. 2 mine:

![Diagram of Quecreek Rescue — plan view, not to scale]

The Yost contractors started the 29 inch (736 mm) rescue drill hole on Thursday evening. The Ingersoll-Rand rotary drill had a DTH hammer. On Friday, 1 a.m., a drill bit was lost and it took four attempts to retrieve it. During the 15½-hour stop, a second rescue drill hole was started on Friday noon. Rescue drill 2 had a 30 inch diameter and used DTH technology as well. On Saturday, its drill bit broke and was lost. Rescue drill 2 remained at 62 m depth and was not restarted until the final rescue through hole 1. Its average speed was 2.3 m/h.

A state police helicopter brought a special grabbing tool to retrieve the lost drill bit in the first rescue hole. The tool was made just-in-time and arrived at Friday 7 a.m. followed by a new 30 inch drill bit on 7 p.m. Due to the larger diameter of the new drill bit, rescue hole 1 had to be re-drilled. After the drill bit got damaged again, another new drill bit was necessary. Only a 26 inch (660 mm) was available but still suitable to drill a diameter suitable for the rescue capsule.
Before the final break-through, the drilling of rescue hole 1 had to be stopped for 6 hours because the water level was still too high. The large-diameter rescue drill hole finally reached the trapped miners on Saturday, 10:13 p.m. A pressure gauge was immediately attached to the pipes to prevent losing a potential overpressure of the underground void. But measurements showed no difference to the atmosphere on surface.

Besides the three small-diameter pilot drills and the two large-diameter rescue drills, eight drainage drill holes were established by Yost and Falcon during the whole rescue mission: Six were drilled from a cornfield into the mains of the mine and two others reached the 1-Right section. Small diameters were drilled at 19.6 m/h while larger diameters took 7 to 12 m/h. As mentioned above, the accessible farm land was an accelerating factor to all drilling operations.

Types and capacities of pumps changed over the whole rescue operation because of changes and replacements. The peak pumping rate was 27,000 gallons (102 m³) per minute. Besides pumps lowered through the drainage drill holes, larger diesel pumps were operating at the mine portals. Pumping was necessary because water kept flowing into the mine threatening the trapped miners and their access to the planned rescue drill holes.

The progress of drainage let the trapped miners reach the small-diameter drill hole again on Saturday night. One hour before the breakthrough of the rescue drill, they could again tap and give the first sign of life after 2.5 days. The small-diameter drill hole could be used again to lower communication equipment and a light stick. “Blankets, rain suits, cap lamps, chewing tobacco, food, water, and a gas detector” (Brady et al. 2003) were put into the MSHA rescue capsule. Shortly before the final rescue, it was the first external supply after three days. The MSHA capsule reached the miners through the large diameter drill hole on Sunday, 12:40 a.m. 15 minutes later, the first miner ascended to surface. The last of the nine trapped miners reached surface on Sunday, July 28th, 2:45 a.m.

From the first day on, stakeholders such as families and media representatives were kept away from the rescue itself and from each other. A nearby fire station was used as an accommodation for the trapped miners’ families whereas media were directed to a parking lot of a shopping center. (Brady et al. 2003) The two parties
received regular information briefings “by MSHA, state and company officials” (McKinney and Urosek 2002).

Several external experts and public authorities enabled the successful rescue. The mutual aid of two surveying and three drilling companies has already been described above as well as the security offered by the police who also escorted the different equipment transports. MSHA provided expertise and equipment like the rescue capsule and their seismic location system. The state of Pennsylvania was prepared for disaster management as well since Flight 93 of the 9-11 terrorist attacks had crashed nearby in 2001. (Fiscor 2002)

“Salvation Army, the Red Cross, the local fire departments, the local restaurants, and neighbors” (McKinney and Urosek 2002) provided food for the rescue teams. 50 Navy specialists were responsible for preparing any over- or underpressure scenario during the breakthrough of the rescue drill. Decompression airlock chambers were brought to the site. In the final rescue they were not necessary because there was only a pressure of 1.2 bars underground.

All Level 4 codes are represented in this case study. Although the Quecreek mine rescue took “only” four days, it provides valuable lessons regarding the rescue of miners trapped underground. The minor depth faced the challenge of possible overpressure in an inundated mine.

4.2.5 Lassing, Austria 1998

The Lassing talc mine was in the Styria province of Austria. The Naistsch Mineralwerke GmbH (owned by Rio Tinto) mined talc until the accident of 1998. Mining too close to saturated soil caused a high pressure gradient between open voids of the mine and adjacent strata. On Friday noon, July 17th, Water and mud broke into the mine and a crater on surface damaged several houses.

One miner (Georg Hainzl) became trapped underground for more than nine days whereas his five colleagues were able to escape. Hainzl survived in a snack chamber 60 m underground. An air pocket formed and remained because the chamber was 2.4 m above the
flooded level. There, Hainzl was able to immediately call for aid by telephone. (Hollmann et al. 2004)

The first inrush left a crater on surface that filled with ground water. About ten hours after the first incident, the increasing pressure caused a second inrush. This inrush killed ten miners who had gone underground. They wanted to make an inspection of the damaged mine, install water barriers and repair pumps 130 m underground in order to rescue Hainzl.

After this second incident, the telephone connection to Hainzl was cut and no access for mine rescue teams to go underground was available anymore. As a result, the new overall rescue strategy comprised ground and water control by pumping on the one hand, and to find and rescue the miners missed underground by drilling on the other hand. The two measures had to start from surface.

The German drilling company “Angers und Söhne” conducted two large diameter rescue drills; one for the snack chamber where Hainzl possibly had survived the second inrush and subsequently one near the backfill shaft where the 10 missing rescuers might have had the highest chance of survival. Another six small-diameter drills were put by the Austrian oil and gas company OMV to examine other potentially “survivable” parts of the mine during the search for the 10 missing rescuers. Their average drilling speed varied between 0.8 and 1.5 m/h.

Hard dolomite overburden was a challenge to the drilling operations (Müller-Ruhe 1998). Furthermore, directional drilling was applied to prevent hitting irrelevant voids of the mine. This would have caused time delay because of cementation at a larger distance etc. Another technological challenge was to keep the overpressure of the potentially survivable voids underground. Thus, drilling operations had to be conducted sealed and pressurized.

For a possible rescue of trapped miners from pressurized voids, special pressure chambers where transported to the mine site. In addition, marine rescue experts from Italy and Germany were available to support rescue under overpressure. (Maier 2009)
Drilling was stopped two times when operation control lost hope to find survivors. On the fourth day, the Austrian government forced the rescue efforts back to work – at least for the psychological effect of further drilling. Nine days after the inrush, the public was told that there was no chance for Hainzl to be still alive. A pilot drill had shown a water-filled room. But the German drilling company made the decision to continue the large-diameter rescue drill for the snack chamber:

Since only the recovery of the dead body of Hainzl was expected at that time, no technical measures regarding a potential overpressure in the snack chamber were applied. They broke through on Sunday, July 26th at 7:30 p.m. Drilling the 62 m with a diameter of 660 mm took 192 hours (0.3 m/h). Surprisingly, the rescuers made vocal contact with Hainzl after the breakthrough. Two hours later, he was brought to surface through the borehole.

Hainzl’s rescue gave new hope for the rescue mission. But not the “backfill” rescue drill or the other pilot drills found any sign of life. Besides drilling, also geophones were used to try to receive signals of the missing miners. In need for total silence, this technology required all other equipment to pause which caused substantial delay for the drilling and pumping operations. Any tracking approach with geophones was unsuccessful.

On August 4th, 18 days after the initial incident, the rescue mission was stopped. The ten missing miners of the first rescue attempt had to be declared dead. The rescue mission itself generated costs of more than 18 million Euro (Hersche and Wenker 1999). The subsequent Figure 22 puts together key aspects of the rescue mission:
In the snack chamber, Hainzl had survived 227 hours in total darkness without food or water. For fear of poisoning he had not drunk any mine water. After the second inrush, he had lost electricity and telephone connection. The chamber’s atmosphere had 2 bar overpressure and temperatures between 12° and 14°C. Hainzl did not panic and dozed most of the time. Instead of calculated 24 hours, oxygen in the chamber lasted for almost 10 days.

On surface, the aid of about 3,000 people had to be coordinated. There used to be confusion concerning the overall leadership of the rescue mission. (Hersche and Wenker 1999) Until the second inrush, there was only an implicit task sharing: The mining company organized workings regarding the mine and the evacuation of the damaged houses. Public authorities including firefighters prepared the assembly of a drilling rig and started dewatering measures such as the bypass of a river around the crater. (Hollmann et al. 2004)

After the second inrush, the mining company remained formally responsible for another two days albeit key persons were lost underground. Then, mining authorities took over the management of the mine rescue mission. Thus, in both phases mining experts led the rescue whereas crisis management professionals were rejected. A fence around the affected area
was not installed until three days after the incident. Thus, in the first days, rescue teams, journalists and bystanders were mixed up around the mine. (Hersche and Wenker 1999)

In the following days, different groups of supporters joined forces, including “the disaster relief agency of the state, the mining team, local political authorities, firefighters, Red Cross, police, and army.” (Hersche and Wenker 1999) Due to the chaotic scenes on surface, a psychologist and two social workers were called in early as well. But they could not handle the situation and also police psychologists had to retreat from the extreme scene. Finally, approved disaster support teams and forty psychologists were working around the mine site.

All the agencies mentioned before brought in their own leaders and even own communication networks. A coordinating headquarter had been established in a nearby restaurant. But in the crucial first days, only two firefighters were sitting there. Their single telephone connection became public and broke down. Instead, inter-organizational communication had to be made by “visits”. (Hersche and Wenker 1999)

Besides the above mentioned Italian and German experts regarding overpressure issues, also mine rescue teams from Western Germany, Bavaria and Hungary came to Lassing. But only the Western German hard coal team was integrated into the rescue efforts. Language and qualification barriers led to the exclusion of the Hungarian team and also the Bavarian team was set on stand-by.

The Austrian army established pontoon-based pumps\(^{30}\) on the “lake” that developed over the crater on surface. Furthermore, they organized shelter and food for the helpers. Within the mine rescue mission, they provided geophone tracking, pressure chambers and cranes for the drill rigs. Assembling communication infrastructure took four days. There was no emergency communication immediately available. (Hersche and Wenker 1999)

The Bavarian mine rescue team tried to enter the Austrian airspace in military helicopters without permission or previous announcement. They were initially stopped. Also the German drill rig was stopped at the border until Austrian

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\(^{30}\) Since one pontoon can move several pumps it was superior to pumps moved by cranes and helicopters, which has also been tried. In addition, wells around the crater prevented more inflow. (Maier 2009)
government intervened. The drilling company had been immediately called by the mining company and assembled the drilling equipment from three different construction sites.

It took more than 24 hours to install all drilling equipment since access to the mine site had to be paved after the crater had destroyed former roads. Mobile service platforms would have accelerated the drilling preparation. (Müller-Ruhe 1998) Regarding equipment, Hersche and Wenker (1999) state: “No resource lists were available. Nobody knew initially where to find special tools and equipment. Special equipment had to be requested through television, representing certainly one of the beneficial aspect[s] of media coverage.”

About 300 media representatives overwhelmed Lassing for almost one month. Trucks and helicopters caused blockages of important access routes for rescue personnel. Furthermore, there was no information policy of the rescue organizers. These unmet information needs resulted in incorrect reports and own search for information by journalists. For the victims’ families, no support center was installed neither. (Hersche and Wenker 1999)

The residents of Lassing and their mayor made own efforts to search for trapped miners. Also mystics, mentalists and impostors started unapproved actions. Hundreds of curious onlookers crowded the rescue site, as well. Other residents of Lassing were directly affected by the mine inundation. Their houses had to be evacuated because of the crater.

As already mentioned, there was high intervention of politics. On the one hand, it opened borders and helped to continue rescue efforts. On the other hand, the question of authority rose several times: When there was little hope for survivors, federal authorities left the scene and local authorities were responsible for the management of the rescue mission. After the “miraculous” rescue of Hainzl, federal authorities raised (unfounded) hope and ordered new drillings.

The only Level 4 code not identified by this case study is the support of trapped miners. This is coherent because rescue teams had no contact to Hainzl since the first day until his rescue on the 10th day of entrapment.
4. CASE STUDIES OF SELECTED REFERENCE MINE RESCUE MISSIONS

4.2.6 Lengede, Germany 1963

The Mathilde iron ore mine belonged to the metallurgical works of "Ilseder Hütte" and was in Lengede, Lower Saxony, Germany. Since it became famous in Germany as the "Wunder von Lengede" ("miracle of Lengede"), the case is named "Lengede" within this study and its databases. In the evening (8 p.m.) of Thursday, October 24th 1963, a settling pond broke into the mine and 500,000 m³ of water and mud flooded the underground workings.

At the time of the inrush, 129 miners were underground. 29 miners died and 79 escaped in the first hours. Three groups of miners became trapped alive: 7 miners were rescued 1 day after the incident, while two other groups' entrapments fit into the scope of this thesis: 3 miners were trapped for 8 days and 11 miners were trapped for 14 days. These two groups are subject to the following single case study.

The mine management registered all escaping miners on surface. Their reports were recorded to get information regarding the number and the location of missing miners. The mine management further contacted drilling and pumping companies. And also the German Federal Railway was warned because the unstable settling ponds were close to some railway tracks. (Schulte 1964)

Stopping the inflow from the settling pond was one of the first priorities of the rescue mission. 40 hours after the initial breakthrough, the plugging of the breaking hole by timber, rock and debris succeeded. One more countermeasure was the decision of the mining authority to keep the compressors running to supply compressed air to any survivors trapped underground. This was crucial to the survival of all trapped miners that were rescued in the following. During the inrush, 34 men became trapped on the 70 m level. 13 drowned while trying to escape. The others retreated to the production heading.

The increasing water level forced them to climb into the goaf. 10 of the 21 men died during the next days because of rockfall and 11 stayed trapped for 14 days in a void of a few cubic meters. Some fresh air flow out of broken compressed air pipes went through the goaf. The existing void in the broken rock of the goaf and the availability of fresh air are two strokes of luck within the "miracle of Lengede". The men’s entry to
the goaf later became blocked as well by more rockfall. The location of the 11 men and the subsequent rescue approaches are visualized in the subsequent Figure 23:

Three other miners became trapped on the 100 m level. They also had to retreat to the heading. Here, solid rock created an air pocket where they stayed until their final rescue after eight days. The water level left about 30 m of open drift at a depth of 80 m. The air pocket was at an overpressure of 1.4 bar (140 kPa). Figure 24 visualizes the situation of the three trapped miners as well as the following rescue attempts by drilling:

During the first hours, the three miners tried to build barricades against the rising water. They also opened valves of the compressed air pipes. Subsequently, the water stopped rising because of the overpressure. But also the cap lamps stopped working after some hours. The miners had to stop walking around and were sitting on wooden boards in the darkness. One of the miners had read about the comparable Oneida
rescue (USA 1963, see p. 31). He kept speaking about this successful rescue and gave hope to his two colleagues. However, the rescue teams on surface did not know the parallels of their drillings rescue strategy to Oneida (Dittrich 1963).

During the first day, the mine received mutual aid of mine rescue teams from neighboring mines and local firefighters. Two ventilation boreholes and the Mathilde shaft were used to go underground. But the mine rescue teams only faced flooded drifts and were not able to find any survivors in these last accessible parts of the mine. As a result, the following rescue efforts were dedicated to drilling technology.

The reports of the escaped miners (see p. 75) were a first indicator for possible locations of trapped miners in other parts of the mine. In a second step, mine plans were evaluated looking for survivable locations: To create air pockets (as described on p. 15), a drift needs to be inclined and of solid rock at the face. Also doctors contributed to these estimates. These initial steps of tracking for trapped miners led to promising drilling spots.

The first three drillings led to the successful rescue of 7 miners after 1 day.\textsuperscript{31} Two more pilot drills were put to locate the largest group of missing miners without success – it was not known that they had retreated into the goaf. Finding the three miners alive on the 100 m level was more promising. The opened compressed air pipes led to air escaping a ventilation borehole nearby which was, besides the surveyors’ assessment, one more indicator of survivors.

Doctors did not know how long people could survive under overpressure. Thus, not only successful pilot drilling was time-critical but also a large-diameter rescue drill hole had to be started immediately. The effects of overpressure on the trapped miners as well as on the drilling operation are given further below (p. 79). The pilot drill for the 3 trapped miners was drilled with the same equipment as the previous ones – a near-surface well of Göttker. This drill broke into the drift in a depth of 79 m after 33.5 hours of drilling (2.4 m/h). Tapping was registered and confirmed three survivors on late Sunday afternoon, October 27\textsuperscript{th}.

\textsuperscript{31} As stated above, this short-term entrapment is not subject to this thesis. The first small-diameter pilot drill (19 m/h) allowed location and communication. The two large-diameter rescue drills were stopped when the dropping water level allowed rescue teams to go into this part of the mine and to rescue the 7 miners with rafts.
After three days without supply, the trapped miners received beverages, food, light and clothes from surface. Communication was established through radio which also allowed tele-medical examination. However, the injection of air had to be stopped to permit radio communication. Since some air was lost underground, it was decided to mainly put air through the drill hole and to limit communication to every three hours. As psychological countermeasures, games and sports magazines were sent to the trapped miners. To keep the dimension of the Lengede rescue mission secret, even a limited edition of a newspaper was printed for the three miners who were requesting information regarding their colleagues. (Dittrich 1963)

Due to the time-pressure, a large-diameter rescue drill (No. 7) was started before the pilot drill had reached and found the 3 miners. A small portable Failing 2500 rig of the Thiele Company reached Lengede on Saturday evening, October 26th and started drilling the next morning. The large diameter of 635 mm was drilled by a rotary drill. But the given power of 103 kW (140 hp) only allowed a slow average progress of 0.8 m/h.

During the slow progress of rescue drill 7 it was calculated (with the aid of the trapped miners) that it would reach the drift above a large loader that was not movable anymore after the loss of electricity underground. Thus, it was decided to start another parallel rescue drill. The drilling company of Deilmann provided an Ideco H 525 rotary rig. This rig had a given power of 552 kW (750 hp) and was the largest mobile deep-drilling rig in Germany 1963.

28 hours after its disassembly 280 km away from Lengede, the Ideco rig started drilling on Tuesday, October 29th at 11 a.m. In only 17.5 hours it reached the casing depth of 60 m at the same time as the Failing rig. Thus, the Ideco drill (No. 8) was equipped with the preventer equipment while drill 7 was temporarily stopped. On Friday, November 1st, 4:30 a.m. (thus 1.2 m/h) it broke through without a leak of overpressure. The trapped miners had retreated to the highest point available and kept a continuous tele-communication to surface during the last two meters of the rescue drill.

Around noon, a mine rescue man reached the 3 trapped miners with a rescue capsule. His role was to support the trapped miners during their entry to the
capsule. Furthermore, he would prevent letting a trapped miner stay alone as the last to go into the capsule. This lesson was adapted from the Dahlbusch mine rescue – the first mine rescue mission that applied a rescue capsule (see p. 30). At 1 p.m. all of them were on surface and stayed for three hours of decompression in the pressure chamber.

The 1.4 bar overpressure of the trapped miners’ air pocket had to be kept during the drilling operations. A decrease of overpressure would have caused an immediate raise of the water level and the death of the miners. Thus, the drilling rigs were equipped with preventers. Furthermore, the breath of the miners had to stay at the overpressure after the rescue, as well:

Overpressure causes a saturation of gases in body fluids and tissue. A fast decrease would have caused a resulting precipitation of enriched nitrogen\(^{32}\) (known as decompression sickness, the bends or caisson disease). Accordingly, a pressure chamber was connected to the rescue drill hole which housed the hoist of the rescue capsule. The miners stayed in the chamber for three hours of slow decompression. A doctor, a technician and the mine rescue man accompanied them.

Lengede was the first time that mine rescue faced the challenge of overpressure. For the drilling operation, experts of the oil and gas industry supervised the drillings and the application of preventers. Besides preventers, the top part of the drilling casing needed to be cemented to seal the drillhole against the atmosphere – one more time consuming measure to keep the overpressure underground. For the pressure chamber and the health of the miners, several doctors and diving specialists were also involved.

During the rescue of the 3 miners, the 11 miners remained undiscovered in the goaf. Besides the 11 survivors, several dead bodies were lying next to them and in the mine water they had to drink. Some refused to drink during the first days of

\(^{32}\) Overpressure leads to dissolved nitrogen in body fluids and cells of the human body. The Lengede rescue led to new facts in medicine: It was not known before, that the dissolved nitrogen stays inactive for eight days under permanent overpressure. A further new observation was that overpressure causes sleep disorder during the entrapment. Weeks and months after the rescue, the miners suffered heavy joint pain because of nitrogen bubbles in bone marrow. (Liebau 1965)
entrapped because they feared cadaveric poison. Although they were freezing, they did not take cloths from their dead colleagues. Only lost hard hats were replaced by those of the dead.

The oldest miner became the leader of the group. He worked as mediator during fights and calmed down fear. The fear of death was omnipresent. Continuous rockfall threatened the miners and caused heavy injuries and painful death over the days. Altogether the situation for the 11 miners was hopeless. They were not waiting in a regular opening of the mine where they could have been found but in loose rock within the goaf.

In the total darkness, some miners faced hallucinations. Furthermore, the group lost sense of time. Nevertheless, darkness was reported to be the heaviest burden during the first part of the entrapment. These psychological burdens overbalanced even somatic needs like hunger. The trapped miners had nothing to eat for ten days. Junghans (1984) stated that the low temperatures of 13°C and the high humidity of 90% supported survival.

After the rescue of the 3 miners, the mine manager stopped the search for other survivors. But some miners had the idea of miners trapped in the goaf and they enforced a last pilot drill. The surveyed point on surface was on a railway track. Thus, the drilling spot was relocated by 2 meters. It was subsequently discovered that the according mine plan was incorrect by another 6 meters and that the following pilot drill drifted 2 meters. The successful hit of the void of the trapped miners within the goaf was again a stroke of luck during the “miracle of Lengede”:

The M60 H drill started on Sunday, November 3rd on 3 a.m. and completed the 55 m long drill hole in 3.5 hours (15.7 m/h). It took 15 minutes before the trapped miners responded the tapping signals from surface. Due to the rounded drift of the drill hole, its outer diameter of 121 mm could not be cased and used. Thus, the drilling pipe remained in the hole and only its inner diameter of 58 mm could be used to send supplies to the trapped miners:

A line with torch, paper and pencil enabled first communication. After 224 hours in darkness, the trapped miners reported to be 10 survivors, however their list of names contained the right number of 11 men. Small bottles of drinks were then sent down before special tubes were designed to send other equipment underground. The tubes allowed the supply of clothes and radio communication. The calorie intake was
carefully increased from 500 to 3,000 kcal. For hygienic causes, urine bags were sent down. Although the trapped miners had already established a latrine corner, some were not able to move anymore.

Furthermore, compass and yardstick permitted simple surveying of the location of the void and the pilot drill by the trapped miners themselves. This should contribute to the definition of the rescue drilling spot. In preparation of the large diameter drilling, the trapped miners also received personal protection equipment against dust and noise.

Small pipes and angles were sent down to increase roof support. The trapped miners assembled shelters against rockfall which was expected to increase during the large-diameter rescue drill. Nevertheless, this light roof support was mainly a psychological counter-measure. Especially plastic blinds were used to screen the miners’ from the view on the hazardous broken rock of the goaf. Afterwards, several of the trapped miners reported that the following 4 days of waiting for the final rescue were psychologically even more challenging than the first 10 days of entrapment without contact to surface. Especially the delays during the large-diameter drilling caused heavy depressions.

Doctors were involved in the rescue of the 11 as well. While overpressure was the primary medical challenge during the rescue of the 3, the 11 miners faced especially hypothermia and malnutrition after ten days without supply. The doctors specified the food which was send to the trapped miners. This food was light and low-salt. Coffee and Tobacco were excluded. Furthermore, the doctors arranged daily consultation hours via telephone. (Stein 1964)

The valuation of the unstable conditions of the void in the goaf led to the decision to establish a second supply drill hole (No. 14). This hole should have a larger diameter to enable transportation of roof support material. Also a jack hammer should reach the miners to allow establishing an access drift to the rescue drill hole. But these plans were subsequently rejected because of the weak condition of the trapped

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33 First plans showed that the rescue drill would reach the depth of the miners 1.5 away from the void. But initial surveying by the trapped miners using a compass was incorrect by 180°. And also the last rescue drill had diverted from the original plan. Thus, plans to establish an access drift from the rescue hole to the trapped miners by mine rescue men were obsolete, which was one more stroke of luck to the successful rescue.
miners. Nevertheless, a pipe should be established to provide fast hardening cement-plastics composite.

At a depth of 62 m the trapped miners felt the air-flushing\textsuperscript{34} of drill 14 and the operators of the drilling company Göttker registered that their rotary drill had missed the miners’ void. However, they were close and it was decided to cement this drill hole. This should cause further stabilization of the broken rock by using the filled drill hole for anchorage.

After the discovery of the 11 trapped miners, the Ideco drilling rig that had already drilled the rescue drill hole for the 3 trapped miners was installed again and started drilling on Monday, November 4\textsuperscript{th} at 3 a.m. The 600 mm rotary rig reached the casing depth of 40 m after 15.5 hours. Due to the broken rock conditions\textsuperscript{35} in the goaf the Deilmann drilling team had to turn to dry drilling. Dry drilling had not been conducted before for such depths and diameters. A corresponding compressor was fortunately under construction (see p. 83). The final breakthrough at a depth of 56 m was achieved on Thursday, November 7\textsuperscript{th} at 6 a.m. (0.7 m/h). Casing for the lower part of the hole was in within hours and the rescue capsule could be lowered.

This time two mine rescue men were lowered to the trapped miners to support the rescue. This was especially to prepare for an eventual collapse of the first rescuer due to the poor hygiene underground. But the two mine rescue men managed the situation. They brought sandwiches to the trapped miners which was the first solid food after two weeks. Most important was the psychological distraction by the sandwiches:

The order of escape was determined by the doctors taking into account medical considerations. But also the trapped miners had argued about this order. The differences between the two lists caused stress even after the arrival of the first rescuer underground. But under the supervision of the rescue teams and the miners’ leader (who announced to be the last of the

\textsuperscript{34} To protect the trapped miners, the drillings were conducted without water flushing which was another innovative approach of this rescue mission.

\textsuperscript{35} The previously conducted pilot drilling (No. 10) provided such valuable know-how about the geology. Furthermore, it was psychologically important to put pilot drill holes which were heard by the trapped miners and which were showing that a search and rescue mission was on its way. (Stein 1964)
trapped to leave the mine), the men calmed down and a rather disciplined rescue could be completed during one hour.

The final rescue of Lengede became a media event. 449 journalists were officially registered. The high public interest is also underlined by the visit of the Federal Chancellor Erhard who spoke to some of the trapped miners through intercom during the rescue mission. This intercom was again provided by media representatives. (Stein 1964; Dittrich 1963)

The transport of drilling equipment was accompanied by police. Also the drilling companies themselves accelerated the assembly of all required equipment. The auxiliary compressor which became necessary for the air flushing of the large-diameter drill was under construction in a German factory (GHH) for a Belgian customer. The air flushing as well as the capacity of the compressor was of new dimension for the mining industry and it is one more stroke of luck to the “miracle of Lengede” that it was under construction near-by and just-in-time. Altogether 950 persons of external companies (e.g. 15 companies of the oil and gas industry) were involved in the Lengede rescue. They supported the 650 men of the mining company itself (Stein 1964).

The only Level 4 code not represented in this single case study is delegation. The mine management was responsible for the full rescue mission and involved external experts from the oil and gas industry as well as the mining authorities from the first day on.

An overview of the two relevant Lengede rescue missions (3for8 and 11for14) is given by the subsequent Figure 25. Only six out of a total of 15 drills are shown here.
4.3 Multiple Case Study Analysis

The single case studies in chapter 4.2 analyzed six major mine rescue missions independently from each other. The single studies were structured by the overall Level 4 codes. The subsequent multiple case study compiles and compares these results. Identified patterns, e.g. based on the Level 4 codes, help to learn overall lessons for future successful mine rescue missions. Patton (2009) defines such synthesis of different qualitative studies as a cross-case analysis. The single case studies are already triangulated from multiple sources. If several of such qualitative studies are subject to another cross-case or multiple study, “high-quality lessons learned” (Patton 2009, pp. 564-566) can be generalized and extrapolated for future programs or guidelines.

Kreps (1991) concludes that improvisation can be the reason for success in a first disaster but that the success in a second one needs derived preparedness. Thus the following multiple case study analysis is divided into three steps. First, chapter 4.3.1 provides an analysis of the distribution of the earlier given Level 4 codes. Then, chapter 4.3.2 orients its cross-case analysis on the equivalent codes (or aspects). Finally, chapter 7 gives comprehensives conclusions as lessons learned and describes the need for more input from disaster management to long-lasting mine rescue missions.
4.3.1 Cross-Code Analysis

The coding procedure has been given in chapter 4.1 and conducted in chapter 4.2. That anticipates parts of the multiple case study analysis because it has been conducted on a cross-case scale. The subsequent Table 11 gives an overview of how the nine level 4 codes are distributed over the six single cases. San José and Quecreek cover all and Lassing and Lengede all but one of the codes. Wangjialing and Beaconsfield lack specific information with only five codes.

<table>
<thead>
<tr>
<th>Level 4 Code</th>
<th>San José</th>
<th>Wangjialing</th>
<th>Beaconsfield</th>
<th>Quecreek</th>
<th>Lassing</th>
<th>Lengede</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case Description</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
</tr>
<tr>
<td>Delegation</td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
<td><img src="image9" alt="Image" /></td>
<td><img src="image10" alt="Image" /></td>
<td><img src="image11" alt="Image" /></td>
<td><img src="image12" alt="Image" /></td>
</tr>
<tr>
<td>External Aid</td>
<td><img src="image13" alt="Image" /></td>
<td><img src="image14" alt="Image" /></td>
<td><img src="image15" alt="Image" /></td>
<td><img src="image16" alt="Image" /></td>
<td><img src="image17" alt="Image" /></td>
<td><img src="image18" alt="Image" /></td>
</tr>
<tr>
<td>Logistics</td>
<td><img src="image19" alt="Image" /></td>
<td><img src="image20" alt="Image" /></td>
<td><img src="image21" alt="Image" /></td>
<td><img src="image22" alt="Image" /></td>
<td><img src="image23" alt="Image" /></td>
<td><img src="image24" alt="Image" /></td>
</tr>
<tr>
<td>Natural Events</td>
<td><img src="image25" alt="Image" /></td>
<td><img src="image26" alt="Image" /></td>
<td><img src="image27" alt="Image" /></td>
<td><img src="image28" alt="Image" /></td>
<td><img src="image29" alt="Image" /></td>
<td><img src="image30" alt="Image" /></td>
</tr>
<tr>
<td>Preventive Measures</td>
<td><img src="image31" alt="Image" /></td>
<td><img src="image32" alt="Image" /></td>
<td><img src="image33" alt="Image" /></td>
<td><img src="image34" alt="Image" /></td>
<td><img src="image35" alt="Image" /></td>
<td><img src="image36" alt="Image" /></td>
</tr>
<tr>
<td>Stakeholder</td>
<td><img src="image37" alt="Image" /></td>
<td><img src="image38" alt="Image" /></td>
<td><img src="image39" alt="Image" /></td>
<td><img src="image40" alt="Image" /></td>
<td><img src="image41" alt="Image" /></td>
<td><img src="image42" alt="Image" /></td>
</tr>
<tr>
<td>Support Trapped</td>
<td><img src="image43" alt="Image" /></td>
<td><img src="image44" alt="Image" /></td>
<td><img src="image45" alt="Image" /></td>
<td><img src="image46" alt="Image" /></td>
<td><img src="image47" alt="Image" /></td>
<td><img src="image48" alt="Image" /></td>
</tr>
<tr>
<td>Technology</td>
<td><img src="image49" alt="Image" /></td>
<td><img src="image50" alt="Image" /></td>
<td><img src="image51" alt="Image" /></td>
<td><img src="image52" alt="Image" /></td>
<td><img src="image53" alt="Image" /></td>
<td><img src="image54" alt="Image" /></td>
</tr>
</tbody>
</table>

The Level 4 Codes of “Case Description”, “Natural Events”, “Preventive Measures” and “Technology” come into view in all case studies. Nevertheless, “Case Description” is not a phenomenon as such but an introductory and connecting tool in the single case studies. In contrast, the handling of natural events, the role of preventive measures (or lessons learned for future application) and the use of applicable technology are occurring patterns.
In his work about community disaster management, Quarantelli (1996) calls such functions which are common to all disasters “generic” (see criterion 2 in the following Table 12). Altogether, Quarantelli defines ten criteria to evaluate disaster management of communities. They are shown in the left columns of the subsequent Table 12.

**Table 12: Transfer of the Case Studies to the 10 Evaluation Criteria after Quarantelli**

<table>
<thead>
<tr>
<th>No.</th>
<th>Criteria</th>
<th>Exemplary Phenomena</th>
<th>Equivalent Codes</th>
<th>Unsatisfied Demands</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Response and agent generated demands</td>
<td>General logistics vs. scenario-specific technology</td>
<td></td>
<td>Infrastructure for emerging groups</td>
</tr>
<tr>
<td>2</td>
<td>Generic functions</td>
<td>Common procedures like search and rescue</td>
<td></td>
<td>Global standards and procedures</td>
</tr>
<tr>
<td>3</td>
<td>Personnel and resources</td>
<td>External experts, effective logistics</td>
<td></td>
<td>Evidence-based leadership</td>
</tr>
<tr>
<td>4</td>
<td>Delegation of tasks</td>
<td>Groups of internal rescue teams and mutual aid</td>
<td></td>
<td>Pre-set organizational structure</td>
</tr>
<tr>
<td>5</td>
<td>Processing information</td>
<td>Internal communication vs. media information</td>
<td></td>
<td>Inter-organizational communication</td>
</tr>
<tr>
<td>6</td>
<td>Decision making</td>
<td>Conflicts regarding tasks of different organizations</td>
<td></td>
<td>Influences of overwork</td>
</tr>
<tr>
<td>7</td>
<td>Overall coordination</td>
<td>“Who is in charge?”</td>
<td></td>
<td>Limits of command &amp; control</td>
</tr>
<tr>
<td>8</td>
<td>Emergent and established behavior</td>
<td>Coordination of own efforts and external groups</td>
<td></td>
<td>Changing organizational behavior</td>
</tr>
<tr>
<td>9</td>
<td>Reports for news media</td>
<td>High number of journalists</td>
<td></td>
<td>Professional press releases and conferences</td>
</tr>
<tr>
<td>10</td>
<td>Emergency operations center</td>
<td>Improvised headquarters</td>
<td></td>
<td>Inner structure and outer relationships of control rooms</td>
</tr>
</tbody>
</table>

Criterion 1 distinguishes two types of demands that need to be met by successful disaster management: The disaster (or scenario) causes specific needs itself which are agent
generated. Transferred to this thesis, an inundation could be an agent that requires specific equipment such as pumps. Thus, needs can change notably from case to case and must agree with the actual tactics to be in line with a specific incident. On the other hand, the response (here a mine rescue mission) to a disaster creates needs itself, such as logistics to supply the rescue teams or families of the trapped miners. They are common to all types of disasters. Since they have a relation to an overall strategy, they can be planned in advance. Thus, the occurring Level 4 codes are response generated, but specific technology to be in line with individual geology is also an agent generated demand within major mine rescue missions.

Criterion 8 evaluates the successful blending of established organizations and emergent groups or behavior. Regarding the scope of this thesis, established mine rescue teams or hierarchical orders of the effected mining company have to face emergent groups of volunteers, journalists or politicians. The single case studies above have evaluated the involvement of external aid as well as the management of different groups of stakeholders.

Emergency operation centers as in criterion 10 are central units and facilities in disaster management. In mine rescue guidelines, they are usually defined as emergency control rooms on surface. Such improvised headquarters have been identified in different single case studies. Quarantelli puts into focus their inner social structure rather than their physical layout. Referring to Quarantelli, the internal communication as well as the relationships to outside organizations are key parameters to successful disaster management.

Altogether the comparison and transfer of community disaster management and mine rescue missions shows interesting parallels. Learnings regarding the matching level 4 codes (as shown in the central columns of Table 12) are put together in the subsequent chapter 4.3.2. However the evaluation of the mine rescue missions shows that several demands of successful disaster management remain unsatisfied (see right column of Table 12). They are subject to the transfer of such principles into future mine rescue missions, which is achieved by the second part of the thesis.
4.3.2 Aspect-Oriented Analysis

The earlier given level 4 codes function again as the major aspects and structure for this subchapter. On a cross-case scale, several individual facts of the single cases are merged to comprehensive observations in the fields of the different codes.

The general case descriptions are descriptive and connecting, and they also provide relevant learnings, especially regarding the causes of the incidents, their scenario and the equivalent location of the trapped miners, and the key time-series of the following rescue missions.

Hopkins (2000) states in his review of disaster research that the initiating causes of disasters can always be traced back to human – or more precisely – management failure. The given case study analyses show almost the same results: In Wangjialing and Quecreek, inaccurate mine plans and planning caused miners to cut into old, flooded adjacent mines. San José and Lassing were caused by mining activities in critical barrier pillars or zones.

All single case studies represent the two major scenarios for long-lasting entrapments (major rockfalls and inundations) which were identified in chapter 2.2. After major inundations, only inclining sealed drifts or locations above the water level can be considered as “survivable”. That also provides a valuable starting point for the search operations of the mine rescue teams. Lengede and Beaconsfield show classic dead-end scenarios as assessed in chapter 2.3. However, major inundations as in Wangjialing or the damage of central infrastructure as in San José can cause entrapments in large areas of an underground mine, as well. Even the multiple escape-ways of a room-and-pillar network can become impassable as the Quecreek case showed.

The analysis of chronological sequences, as one of the time-series analyses recommended by Yin (2014, p. 154), shows important principles of successful mine rescue missions:

- The search for the trapped miners needs to be done before the actual rescue (e.g. large-diameter drilling) can be started. The same applies for external supply of food and communication to the trapped miners.

- A successful search for miners is always followed by suitable rescue efforts. In Lengede and Lassing hope for a successful rescue was temporarily lost by some officials but different stakeholders like mine workers or politicians led to a successful continue of drilling operations.
- In flooded mines, rescue missions might only be completed after a critical water level is reached. Other characteristic intervals of “waiting” are for signs of survival trapped miners, for the preparation of drilling sites, for the repair of equipment, or for a final rest in decompression chambers.

- The time of search is characterized by information deficiencies of the rescue teams and a time-critical fight for physical survival by the trapped miners. The time until the final rescue can be used to support the trapped miners but technological challenges and delays are substantial psychological burdens for the miners.

Especially with respect to technology, important countermeasures to the critical waiting intervals given in the third point of the above written time-series analysis are parallelization and redundancy. As achieved in Quecreek, surveying and collar preparation of drilling sites can be done while the transportation of the actual drilling equipment is still going on. In all inundation scenarios, stopping the inflow and draining the flooded mine were parallel efforts to the drilling operations. Then accordingly life-critical technologies of pumping and drilling should be applied redundantly: Parallel drilling of several drainage, supply and rescue drill holes decreases the risk of equipment failure or unforeseen geological circumstances.

A pre-assessment for the preparation of successful search or tracking measures is important. Thus, accurate mine plans and knowledge of the underground workings and shift plans are an important preventive measure. Also medical and geological expertise must be included in these early investigations. The potentially survivable locations identified in this procedure are then most commonly examined by small-diameter drill holes. In addition, signals from the trapped miners themselves can be registered by means of tapping on metal pipes (see Wangjiaveling) or air bubbles out of intentionally broken compressed air lines (see Lengede).

After successful tracking, the small-diameter drill holes immediately become supply channels to support the trapped miners. While Water, first aid and nutrition have top priority, the single case studies also show the significance of the psychological effect of contact to surface. Family communication and an exchange of information regarding the progress of the rescue mission satisfy the primary demands of trapped miners.

During the 69 days at San José, the miners even received trainings in exercising, first aid, and dealing with the media. In Lengede, light roof support and edited newspapers were sent
underground to cope with the extreme psychological pressure of the trapped miners. The actual rescue can also be supported by the trapped miners themselves, e.g. by removing cuttings from the pilot drill hole or surveying the remaining openings underground. Such work schedules as well as special lighting help to create a relatively normal day-and-night rhythm.

**Natural events** can substantially influence such support operations. In the inundated mines of Quecreek and Lengede, **air injection** was the most import supply from surface to underground. Sealed openings bare the risk of oxygen deficiency which can be compensated by injection of fresh air. This additional quantity of air can also be heated to prevent hypothermia and the induced overpressure helps to push back the water. Keeping air compressors running, also for the regular compressed air system is an important lesson to apply when dealing with inundated mines. However this priority can make alternative supply or communication through one small-diameter drill hole impossible.

Major collapses cause resulting complicated and unforeseeable **rock mechanics**. Unstable rock conditions notably hampered the rescue missions of Beaconsfield and Lengede. Secondary collapses or inrushes are a major threat to mine rescue teams that made the decision to go underground, as it was the case in San José and – fatally – in Lassing. Another natural constraint was the high concentration of methane during the Wangjialing rescue.

Representatives of the effected mining company, who know best the mine’s geology, should early permit **external aid** to be in line with such challenges during major mine rescue missions. At all regarded cases of inundation, diving or navy specialists supported the mine rescue teams in their decisions and the maintenance of overpressure. In general, diversified but specific inclusion of external experts is a key for success.\(^{36}\)

Public authorities like police, fire fighters and army can support the complex logistics of a long-lasting rescue mission. Red Cross or neighboring restaurants can provide food and shelter for supporting mine rescue teams and families at a larger distance. Here, professional

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\(^{36}\) 20 different companies were involved in the San José rescue whereas 950 external persons contributed to the “miracle” of Lengede. However, language or qualification barriers and a missing overall coordination can also decrease the efficiency of a rescue mission – as seen in Lassing. The role of central leadership will be further evaluated in the progress of the thesis.
psychological and medical support needs to be guaranteed, as well. Specific know-how regarding confined space can be shared with institutions like NASA (as in San José). Oil and gas contractors are experienced in fast and deep drilling operations (see Lengede) and central mining authorities can provide special equipment as MSHA does in the U.S. (see Quecreek).

San José, Wangjialing and Lassing were more or less fully managed by external experts and the mining company retreated (or was removed) from the delegation of responsibilities. In Quecreek and Lengede, the mine management remained responsible during the rescue which accelerated decisions during the time-critical inundations. But they involved external experts from the first day on.

In San José, technical decision making was achieved by a small engineering team around the leadership of Chile’s mining minister Golborne. Roles were clearly specified under the politicians and the mining engineers of the supporting mining company of Codelco. Command centers based on prior response planning were put up to coordinate rescue efforts at Wangjialing and Quecreek. The fire fighters of Lassing tried the same but communication networks broke down and inter-organizational exchange of information was based on “visiting each other” (Hersche and Wenker 1999).

The vast amount of external support makes logistics another crucial field of long-lasting mine rescue missions. The remote site of Wangjialing and the surface destructions of Lassing hampered fast access to the site. The open farm land of Quecreek, on the other hand, facilitated drilling. For more challenging conditions on surface Müller-Ruhe (1998) recommends mobile service platforms to accelerate drilling preparation.

As seen in the time-series analysis above, the early order for special equipment like drilling rigs or pumps is essential. The mining company itself should have personal contacts as seen in Quecreek, Lassing and Lengede. As already mentioned above, police and army can escort important transports or maintain whole supply chains to critical harbors or airports. Politicians must be informed as well to prevent delays at international borders as seen in Lassing.

A major mine rescue mission has several stakeholders which require infrastructure and information. They have to be included into the overall management. Experts offer aid while the miners' families require it. Quarantelli (1996) provides a typology of groups (Figure 26) which are possible during a crisis or disaster:
The mining company can be seen as the Type I group, at least when it has trained mine rescue teams and clear management procedures available. This established organization becomes larger (Type II) when external experts help to fulfil drilling or surveying tasks which are on the one hand a regular task for a mining company but of new dimension when they become life-critical in the true sense of the word.

Type III describes the phenomena when old relationships, e.g. to the adjacent owners or residents, point non-regular incidents. As an example, surface damages destroyed houses of Lassing residents and the mine management of Lengede warned the federal railway which had tracks near the unstable settling pond. Also mining authorities are part of such an extending organization when they provide equipment, expertise or even leadership.

Type IV can be seen as the largest challenge in disaster management because new relationships touch tasks that are not regular. The case studies identify media, politicians and families as the most prevalent emergent groups. They require resources and aid but can also have positive impact on the rescue mission. Professional psychological support to the miners’ families is important. Then, under stable conditions, they can become themselves a psychological support to the trapped miners.

The fate of the miners’ family makes a major mine rescue mission an international media event. Especially Lassing showed the effects of unsatisfactory stakeholder management,
when journalists caused blockages of important access routes and telephone lines and started own investigations on the unsecured site (Hersche and Wenker 1999). On the other hand, television was used to organize special equipment (see Lassing and Lengede). The media coverage increases again the political dimension of a major mine rescue mission. A good integration causes benefits such as financial support, open borders for international help, and moral or practical leadership.

It becomes clear that the different emergent groups (Type IV) are less important to the operational rescue. Thus, they must be isolated from each other and the groups I and II which commonly make the core of the technical rescue. Such a separation has to be arranged early both technically (fences and access control) and organizationally (persons in charge, information flow) as it was achieved in Quecreek for example.

**Preventive measures** which were actually installed were the refuge chambers of San José (food and water) and Lassing (telephone). The rescue missions of Wangjialing and Quecreek were optimized by a public emergency response structure. **Learnings** for possible future survival were achieved regarding the positive group dynamics in San José and Lengede, where leadership and democracy led to relatively high discipline and moral. And also the success stories given and published here could enhance hope to survive such extreme situations of hunger and darkness.
4.3.3 Lessons Learned

The different qualitative case study analysis approaches lead to the subsequent list of ten major principles regarding long-lasting missions to rescue miners trapped underground:

1. Major rockfalls and inundations, commonly caused by human failure, can cause long-lasting entrapments of miners underground – even in modern mine layouts.

2. A pre-assessment provides valuable information to concentrate the search for trapped miners.

3. Parallelization is the key to accelerate critical sequences of the rescue mission, such as surveying and transport or drilling and draining.

4. Drilling and pumping are critical technical steps and should thus be conducted redundantly.

5. Psychological support to the trapped miners is as important as their physical survival.

6. Air injections and the maintenance of the regular compressed air system increase the chance of survival of trapped miners.

7. Unstable rock conditions hamper rescue operations and pose high risk to entering rescue teams.

8. External aid of experts in required technological or medical support must be early integrated into the rescue efforts of the local mining company as well as the related logistics.

9. Media, politicians, and families are important emergent groups during a disaster which need support and infrastructure, which have to be moved apart from the inner rescue, but which also can improve rescue efforts when they are correctly integrated into the overall organization.

10. Emergency provisions and communication systems in inclined points of the mine are preventive measures regarding long-lasting entrapments which are – in principle – survivable.

The interaction of these factors distinguishes the outcome of a major mine rescue mission. Such a list of qualitative facts is not a prioritized list “to follow, but rather a mosaic to create” (Patton 2009, p. 502). The logistics of people and equipment and the positive interaction of different groups also make a mark on the need for more disaster management approaches into mine rescue.
Table 12 (see p. 86) has already compared case study results and the disaster management principles of Quarantelli. The right column’s demands are not or not fully satisfied by the achieved lessons learned. Also the comparison of the mine rescue case studies with the disaster observations of Auf der Heide (1989) show interesting parallels:

- Disaster response is usually multi-organizational and includes several public and private agencies.
- Disasters frequently comprise “only” a small share of serious injuries.
- There is a strong connection between coordination and communication problems.
- Volunteers do not know if they are needed and possibly over-respond.

Assembling qualitative methods, mine rescue data and community disaster observations has shown a need for more implementation of disaster management principles into mine rescue. Thus, the subsequent chapter 5 will identify and transfer suitable approaches into mine rescue. Together with the already achieved lessons learned they contribute to the thesis’ comprehensive mine rescue management definition.
5 Transfer of Disaster Management Approaches

Chapter 5 collects input of disaster management for the thesis’ scenario of long-lasting mine rescue missions. Disaster management can be seen as an independent discipline and field of research. Mine disasters are consciously excluded from the subsequent investigations to let mining learn from other approaches. Thus, man-made disasters such as terrorist attacks or nuclear power plant failures as well as natural disasters like tsunamis or earthquakes are of interest. They cause chaos which requires extraordinary efforts in management which can provide valuable lessons or even standards to be transferred to major mine rescue missions.

Chapter 5.1 introduces corresponding definitions of disasters and emergencies and provides comparisons and parallels to mine rescue. The structure of chapter 5.2 is again based on Quarantelli’s ten criteria for successful disaster management and shall fill the identified gaps during the major mine rescue missions that were analyzed in the case studies before. Accordingly, ten sub-chapters introduce principles in planning and response such as logistics, stakeholder management or leadership. The results compiled here are based on a broad look into disaster management literature. Finally, chapter 5.3 transfers the identified disaster management approaches into the specific circumstances and needs of mine rescue. Thus, chapter 5 creates valuable input out of non-mining disaster management for the thesis’ mine rescue management concept.

5.1 Definition of Terms

To define the term disaster, Alexander (2012) distinguishes four levels of emergencies: The first level is subject to regular procedures such as an ambulance service after a single car crash. The second level emergency demands resources of a whole community or company. As a further step-up, a third level emergency becomes a regional or multi-organizational disaster. The final level is national or international disasters with necessary governmental involvement or international aid. Thus, coordination efforts increase with the degree of emergency level. The prior case studies of mine emergencies usually fulfil the third level of Alexander’s definition but possibly require governmental or international support as in the final level.
Referring to Simonovic (2011), disaster management comprises the four steps of “mitigation, preparedness, response, and recovery” (p. 30). Especially preparedness and response are important within the scope of this thesis. Preparedness has to be seen in the anticipative organization of resources and response procedures. The response itself takes place during the disaster and comprises key steps like search and rescue but also support functions such as communications, sheltering and logistics. (Simonovic 2011)

The mining industry applies different definitions. MSHA refers to the number of fatalities which have to be at least five to fulfil their definition of a disaster (Brnich, Jr. and Kowalski-Trakofler 2010). NIOSH speaks of “a significant toll in human lives” (p. 1) but also explicitly includes entrapments of miners alive in their definition of underground mine disasters. The resulting response possibly requires six different stages which can be “hazard control, evacuation, escape, survival, rescue, and recovery” (p. 12). Here, evacuation follows the regular exits whereas escape refers to alternative routes when the regular evacuation is blocked. Rescue is locating and releasing trapped miners whereas recovery refers to collecting dead bodies. (Commission on Sociotechnical Systems, National Research Council 1981)

5.2 Prevalent Principles

The comparison of the cross-case analysis and criteria of disaster management after Quarantelli, as summarized in Table 12 (see p. 86), has shown certain gaps in mine rescue which represent needs for implementation of disaster management standards. The subsequent Table 13 shows this need in the right column. On the left, corresponding transfers of disaster management are shown. They build the sub-chapters of this chapter and provide input of disaster management literature.
Table 13: Input from Disaster Management

<table>
<thead>
<tr>
<th>Chapter No.</th>
<th>Chapter Title</th>
<th>Criteria after Quarantelli</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2.1</td>
<td>Disaster Phenomena</td>
<td>Emergent and established behavior</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Planning for Disasters</td>
<td>Generic functions</td>
</tr>
<tr>
<td>5.2.3</td>
<td>Incident Command System</td>
<td>Overall coordination</td>
</tr>
<tr>
<td>5.2.4</td>
<td>Coordinated Incident Management System</td>
<td>Delegation of tasks</td>
</tr>
<tr>
<td>5.2.5</td>
<td>The Scope of Leadership</td>
<td>Personnel and resources</td>
</tr>
<tr>
<td>5.2.6</td>
<td>Decision Making</td>
<td>Decision making</td>
</tr>
<tr>
<td>5.2.7</td>
<td>Stakeholder Management</td>
<td>Reports for news media</td>
</tr>
<tr>
<td>5.2.8</td>
<td>Logistics</td>
<td>Response and agent generated demands</td>
</tr>
<tr>
<td>5.2.9</td>
<td>Communication and Information</td>
<td>Processing information</td>
</tr>
<tr>
<td>5.2.10</td>
<td>Control Centers and Posts</td>
<td>Emergency operations center</td>
</tr>
</tbody>
</table>

5.2.1 Disaster Phenomena

Disasters, in contrast to emergencies, show several properties that can be seen in major mine rescue missions as well. Table 14 gives an accordant overview of phenomena identified by Jackson et al. (2004)³⁷:

Table 14: Disaster Phenomena in Mine Rescue

<table>
<thead>
<tr>
<th>Phenomena after Jackson et al. (2004)</th>
<th>Equivalents in Mine Rescue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long duration</td>
<td>Long-lasting entrapments lasting longer than minor mine rescue duties, as seen in Lengede</td>
</tr>
<tr>
<td>Multiple hazards</td>
<td>Risk of methane and oxygen deficiency in an inundated coal mine, as seen in Wangjialing</td>
</tr>
<tr>
<td>Range of capabilities</td>
<td>Challenges of pumping, drilling, overpressure, psychology at the same time, as seen in Quecreek</td>
</tr>
<tr>
<td>Variety of incoming volunteers and supplies</td>
<td>Mine rescue teams, drilling experts and volunteers from different countries, as seen in Lassing</td>
</tr>
<tr>
<td>Damaged infrastructure</td>
<td>Collapsed mine entries and ventilation systems, as seen in San José</td>
</tr>
</tbody>
</table>

The different types of emergent groups during disasters have already been discussed and transferred in Figure 26 (see p. 92). The coordination of own efforts and those of external

³⁷ Jackson et al. 2004 also name large geographic scale and a large number of killed people which are not necessarily a property of long-lasting entrapments as discussed in chapter 5.1.
groups has been necessary in several case studies. McMaster and Baber (2012) bear in mind that a common intent of the participating groups or organizations cannot be presumed. Unclear responsibilities and unawareness of different procedures are example phenomena during crises. Social, organizational and technological barriers possibly hamper the coordination of multi-agency response. Formal structures and procedures can be challenged by the initial chaos of an unplanned situation. (McMaster and Baber 2012)

Accordingly, Auf der Heide (1989) describes how a disaster causes changing organizational behavior: Organizational structures and responsibilities of regular emergency procedures possibly have to be changed during disasters that affected the whole organization. New demands of unforeseen capabilities can require other agencies to join the scene. This might also include participants who usually do not respond to emergencies; for example, drilling experts from the gas industry were told to conduct mine rescue drillings. Furthermore, multi-agency approaches can go across jurisdictional and national borders. Such phenomena result in a new emerging organization that requires the following of disaster management approaches.

5.2.2 Planning for Disasters

Fundamental principles of disaster management are broadly discussed in corresponding literature. Table 15 puts together central principles out of recognized works. The Civil Contingencies Act is UK legislation of 2004 and was analyzed by McMaster and Baber (2012). FEMA is the Federal Emergency Management Agency of the United States as reviewed by Blanchard et al. (2007). The last four columns on the right represent recommendations of acknowledged researchers in the field of disaster management.
Table 15: Common Principles of Disaster Management

<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Preparedness – multi-agency anticipation of roles and demands</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anticipation – risk-driven assessments and decisions</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integration – inter-organizational coordination and collaborative relationships</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Coordination – subsidiarity also on low levels of stakeholders</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuity – quickly restored routines; continuous preparedness planning</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knowledge-based – scientific evidence instead of myths</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comprehensive – consider all risks, phases and stakeholders</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexibility – innovative and improvised actions, no pre-planned details</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

In addition and besides others, the references individually state the following clear principles:

- Planning should put into focus moderate size incidents. (Auf der Heide 1989)
- Own efforts and capabilities of affected communities must not be underestimated and must be supported by an organizational framework. (Kreps 1991)

Table 15 clearly shows that coordination of multi-agency (or inter-organizational) efforts is a central principle and requirement in disaster management. Alexander (2012) and McEntire (2007) come to the same result in their studies of emergency management. Quarantelli (1996) and Kreps (1991) see mutually and timely agreed cooperation as the key to success as

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38 This is in contrast to Heath (2001) who recommends worst case scenarios as planning criteria. But putting moderate size incidents into focus corresponds to the prior observations of this thesis as discussed on p. 95.
well and also favor it over military styles of command and control which are going to be discussed in chapter 5.2.3.

The real planning procedure in preparation of a disaster management approach shall have the previously discussed principles. Especially the last point of Table 15, *flexibility*, is particularly stressed by all cited experts. The high individuality of disasters makes full procedures obsolete. An individual action plan can only be prepared during the disaster itself. Disaster management can just prepare a framework to efficiently include know-how and cooperation into the fast decision for a strategy to be in line with the incident’s requirements.

### 5.2.3 Incident Command System

The Incident Command System (ICS) is a broadly used approach in disaster management. ICS was developed after a series of wildfires in California 1970 to coordinate response of federal, state and local agencies (Auf der Heide 1989). According to Christen et al. (2001), the ICS was subsequently renamed to “Incident Management System” to emphasize its coordinative approach rather than its hierarchical structure. However, most disaster management literature refers to ICS.

Four main sections reporting to the overall incident commander make the organizational structure of the ICS. The corresponding organigram is visualized in Figure 27:

![Organizational Structure of ICS](image)

*Figure 27: Organizational Structure of ICS (after Jackson et al. (2004))*

The incident commander executively coordinates the overall organization. He is supported by command staff like officers for liaison, public information or safety. Operations are organizationally in line and conduct the technical response work as such. The three other
sections are more of staff type: Planning collects information about the incident and provides technical data as well as approved advice of specialists. The planning process further creates short-term and long-term plans for operations and tracks resources. Logistics provides service such as communications and food as well as support such as equipment and supplies, which are necessary to manage the incident. Finance approves such purchases and keeps records. (Auf der Heide 1989; Christen et al. 2001)

This ICS structure is flexible and modular. Depending on the complexity of the mission, each section can be removed or sub-divided into more branches. If a section is not activated, the command becomes responsible for its specific functions. To maintain unity or chain of command, expansion would be top-down to guarantee that each reports to one supervisor. This flexible sub-dividing of expanded tasks also helps to keep a manageable span of control. Again depending on the complexity, each supervisor leads three to seven sub-ordinates. (Everly, Jr. et al. 2008; Auf der Heide 1989)

Another important ICS principle is unified command. Major disaster response usually comes from multiple agencies. They respect a lead agency to set the incident commander but they are still able to participate in decision making. Their top leaders make a team of command and agree an overall strategy. Common terminology further supports such inter-organizational cooperation. (Everly, Jr. et al. 2008)

While fostering inter-organizational cooperation, ICS still keeps agency autonomy. Command might be delegated to one organization but each stays jurisdictionally self-dependent. To improve communication and safety at the same time, comparable agencies of disciplines are designated to same sections or tasks. This principle of ICS is called unit integrity. (Auf der Heide 1989)

ICS provides a flexible framework for disaster management. Referring to Auf der Heide, ICS is based on modern management concepts and provides an effective system for the coordination of multi-organizational operations. However, Quarantelli (1996, p. 12) states that “Control is not coordination”. MSHA’s “Mine Emergency Command System” is an adaption of the ICS to the mining industry. Here, Alexander et al. (2010) criticize that the unified command hampers fast decision making because the leading mine operator needs approval for his rescue plan by MSHA.
5.2.4 Coordinated Incident Management System

The case studies showed a notable need for the delegation of tasks and groups. Disaster management shall provide applicable pre-defined organizational structures. The already introduced Incident Command System (ICS) provides such a structure. However, the following chapter will also put into focus an alternative approach – the Coordinated Incident Management System (CIMS).

CIMS was originally developed in 1998 by New Zealand’s Fire Services. Its principle structure is visualized in the subsequent Figure 28. CIMS is comparable to the basic ICS structure (see Figure 27 on p. 102) but does not include a separate financial section. However, control (by means of coordination) replaces the command character of ICS. On a multi-agency level, control is organized horizontally by an approved action plan whereas the single agencies reserve the right for vertical command (The Royal Commission 2012).

An extended structure of CIMS suitable for large incidents can be seen in Appendix 4. This organigram is based on New Zealand’s CIMS guideline (Ministry of Civil Defence and Emergency Management 2005) as the following role explanations:

The Control section is led by the Incident Controller who approves plans and strategies and maintains a management structure. He or she establishes liaison and cooperation to internal and external partners and stakeholders. Three staff officers support the Incident Controller:

- The Safety Adviser makes sure the safety of involved persons while participating in the planning process. The Information Officer coordinates a consistent information policy and provides information to media and other stakeholders after approval of the Incident Controller. A media center, guided tours, and a log of reports and decisions are part of his or her overall

![Figure 28: Organizational Structure of CIMS (after The Royal Commission (2012))](image-url)
media strategy. In contrast, the Liaison Officer is the contact point for internal and inter-organizational communication.

The Planning Intelligence Manager collects and analyzes information to prepare Planning meetings. Mapping, records and personnel change-over plans are important support to the control team and the management of operations and logistics. The Planning Intelligence Manager supervises four unit leaders. The Situation Unit Leader analyses possible incident behaviors and makes applicable strategies to deal with possible outcomes. The Information Intelligence Unit Leader provides information regarding the incident for internal and external stakeholders which are published in cooperation with the management team. The Management Support Unit Leader does administration and communication duties. Finally, the Resources Unit Leader overviews all demands and orders or resources and the deployment times of teams and equipment.

Operations to resolve the incident are led by the Operations Manager. Resources and cooperation are put in sequence to fulfil the key tasks. Progress as well as identified risks is regularly reported to the Incident Controller. Subordinates of different agencies or competences are installed with respect to the specific needs of the individual incident.

The Logistics plan of personnel, equipment and infrastructure is developed by the Logistics Manager. Acquisition, transport and storage procedures are further supported by up to seven subordinate unit leaders. The Catering Unit Leader plans and provides nutrition for the involved people. Planning, installing and maintaining communication systems are the responsibilities of the Communications Unit Leader while the Facilities Unit Leader assembles temporary shelters for persons and equipment involved during the incident. The Supply Unit Leader organizes missing equipment or specialists identified by other leaders of the logistics section. The Ground Support Unit Leader is responsible for transportation and traffic around the incident scene. Medical support is managed by the Medical Unit Leader and the Finance Unit Leader acquires or hires materials and overviews insurance and compensation issues.
5.2.5 The Scope of Leadership

Despite all efforts in planning and organization, response to disasters will always be spontaneous and managers will have to improvise to a certain extent (Waugh, Jr. and Streib 2006). Thus, leadership is necessary to coordinate response operations. DuBrin (2013, p. 294) provides a corresponding definition: “Crisis leadership is the process of leading group members through a sudden and largely unanticipated, intensely negative, and emotionally draining circumstance.” He sees leadership as the interpersonal (non-administrative) and, furthermore, the most crucial part of management. Referring to DuBrin, the manager’s key attributes for leadership are

- Knowledge, intuition and common sense,
- Creativity regarding new solutions, and
- Insight into people and situations to assign the key roles.

Useem (2011) gives more principles for leadership:

- Formulate an easily understandable strategy including short- and long-term vision.
- Diminish over-optimism and stay open for new ideas.
- Build a small, but diverse advisory team capable of the primary challenges.

The consultation of such a group39 before the leader’s decision is defined as a “participative style” which DuBrin (2013) classifies as suitable for non-regular tasks for motivated teams which clearly is in line with major mine rescue missions. This approach agrees with evidence-based management which is going to be introduced in chapter 5.2.6. To keep the resulting network manageable, the “span of control” out of the earlier mentioned ICS (see 5.2.3) keeps the number of subordinates for each leader to a limit of seven.

However, other constraints to effective leadership (and good decision making) during crises have to be seen in overwork and sleep deprivation. A NIOSH study (Kowalski-Trakofler and Vaught 2012) has identified much relevance as well as insufficient consideration within the field of mine rescue. Referring to Harrison and Horne (2000), fatigue impairs innovation and

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39 The need to include external experts to mine rescue management has also been identified in the case studies before. Waugh, Jr. and Streib (2006, p. 134) state further: “Collaborative networks are a fundamental component of any emergency response.”
mood and enhances inflexibility and distraction of decision makers. Thus, sufficient daily sleep, as the best countermeasure, has to be guaranteed to all people involved in a long-lasting mission.

The earlier introduced CIMS (see 5.2.4) provides a plan for 12 hour-shift changeovers. A simplified version can be found in Appendix 6. This guarantees for systematic changeover. Each section or team meets the replacing one for a meeting before the change. To maintain the progress of the whole mission, these meetings and changeovers are divided into four separate response groups in subsequent time frames of 30 minutes. Furthermore, a central briefing takes places before the whole changeover procedure. (Ministry of Civil Defence and Emergency Management 2005)

5.2.6 Decision Making

Disasters cause unpredictable, dynamic and chaotic situations where decision makers have to process large but fragmentary data in a short time (Thompson et al. 2006). The case studies have further shown inter-organizational issues and information flow limits. Life-threatening scenarios require decisions which must be fast but also accurate. In contrast to the decentralized operations, decision making needs to be centralized in disaster management (Kapucu 2006). Different pillars can and must support decision making during crises. Figure 29 gives an overview of possible decision support factors which will be discussed below:

![Figure 29: Decision Support](image)

Janis (1989) recommends dividing a complex problem or decision into smaller sub-problems. Experts on the equivalent single fields should be available as soon as possible. Such *advisors* increase confidence and thus accelerate important, central decisions

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40 The different Level 4 codes can be seen as sub-problems or issues to divide the primary goal of rescuing trapped miners into sub-problems like technological applications, stakeholder management and logistics.
Another important source for decision making is current information out of the different areas of the mission. Tuler (1988) recommends horizontal communication links to the management instead of sending important data or requests vertically through hierarchies. However, a lot of information is already available before any incident (Brady et al. 2012) and must be integrated into comprehensive emergency procedures. Besides such important inputs, parts of key decisions remain to the intuition of the key responsible person, which again legitimizes leadership as described in chapter 5.2.5.

Systematic lessons learned as provided by the case studies prepared a fifth pillar of decision making in crises which is evidence-based management. Rousseau (2005) defines it as “translating principles based on best evidence into organizational practices” (p. 256) and sees evidence-based management as “a paradigm for making decisions that integrate the best available research evidence with decision maker expertise” (p. 258). A database of lessons of the past, both positive and negative, as scientific evidence facilitates decisions and helps to prevent repeating mistakes (Therrien and Wybo 1995).

5.2.7 Stakeholder Management

The case studies show a large occurrence of different stakeholders during major mine rescue missions. Besides media as a key challenge also mine rescue teams, external experts, adjacent owners, mining authorities, families and politicians have been identified in chapter 4.3.2. Maier (2009) additionally states volunteers, curious onlookers, justice and partners of the affected company (like owners or banks) as further stakeholders of a crisis. A mine operator should prepare a comprehensive list of them before any incident (Hartley 2012).

As seen before, entrapments of miners underground are rare but dramatic in mining, and, as a result, generate vast media interest. Media representatives represent an important demand factor during disaster because they require both information and infrastructure. This can cause blocked transportation and communication systems as well as lost time for disaster managers or even rescue personnel. Thus, such interactions have to be integrated into disaster preparedness planning.

At an early stage, infrastructure like electricity, catering and housing must be considered, e.g. supported by relief organizations outside the rescue area. The management should
further assign one contact person like a corporate spokesperson experienced in public speaking and writing. This person must publish an early press release with short information regarding the incident, its consequences, the primary strategies and the progress of operations. This early, first announcement should be followed by regular press conferences or releases two times a day. Here, the spokesperson can also operate as a moderator when management representatives are available to address some queries from the media. A fixed time plan and a list of participants are recommended. (Hermülheim 1999; Alexander 2012; Schön et al. s.a.)

Auf der Heide (1989) further differs between three types of media with different needs and behavior: local, national and international. The case studies have shown that major mine rescue missions cause a stir in all types of media. Local news attends all stages of a disaster and is interested also in details such as names of missing persons. National media more looks on unique records and dimensions or touching stories. Internationally, the focus is put into general figures and effects – e.g. on affected markets or safety laws and standards in the specific country. All these needs are to be met in the press conferences. On the one hand, national TV stations possibly dominate local journalists but on the other hand, especially these local representatives could be integrated into disaster planning before an incident to be a first or even privileged and trust-worthy contact person. (Auf der Heide 1989; Hermülheim 1999)

Such a liaison position could also be covered by local politicians who usually know the company, its management but also the employees or their families. Hermülheim (1999) recommends integrating local politicians at an early stage whereas politically responsible persons or institutions possibly operate differently. Long-lasting rescue missions with hope for success also attract representatives of national politics. Since this is inevitable, short tours with journalists should be organized when possible.

Another group of stakeholders are the mine employees and the (potentially corporate) mine rescue teams. With respect to a one-voice policy to the media, it is important to make sure discretion between the miners. They need to be informed because they might be worried about their trapped colleagues or shocked after a possible escape but details concerning the

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41 A template for a first press release, based on Schön et al. s.a., can be found in Appendix 5.
incident are only to be told to media by the specified spokesperson. Furthermore, local miners can be part of the rescue missions because they are *familiar with the mine* and can operate as guide for external rescue teams or approved media tours.

The most sensitive and potentially most important group of stakeholders is the families of the trapped miners. Here, the San José rescue can be seen as a positive benchmark where the families lived in a makeshift camp (“camp hope”) with 33 private tents, catering and sanitary facilities, a school, security, communication infrastructure and psychological support (Jordán et al. 2011). Same as for journalists, an unsatisfactory information policy would cause collapsing communication and traffic infrastructure (Auf der Heide 1989). An information center and a central contact person are again a certain need. Although such needs are comparable to those of the media, the different groups need to be kept *isolated* from each other to protect privacy and the rescue mission itself. The inner zone of the rescue is reserved for key operations and thus protected and controlled. Families and journalists are to be directed to separate protection areas, as analyzed in chapter 4.3.2.

### 5.2.8 Logistics

The case studies pointed, as defined by Quarantelli and shown in chapter 4.3.1, response generated demands like general transportation issues as well as agent generated demands like specific *spare parts* for crucial drilling equipment. Although parallel and redundant strategies are highly recommended to rescue trapped miners, mine rescue missions can come to the point where one piece of machinery is crucial to the success. This can be the fastest drilling rig or the strongest pump. Accordingly, Russell et al. (2011) states, “The more essential the item, the more important it is to have a spare readily available.”

Regarding response generated demands, the case studies identified the need for infrastructure for emerging groups like media and families (see 5.2.7). The set of the required *shelters* is determined by the number of people and their expected duration of stay. Long-term shelters require childcare, medical services and transportation facilities like parking spaces. As derived in chapter 5.2.7, security arrangements have to guarantee certain zones in order to isolate stakeholder groups like families and media from each other. The shelter itself can be army tents, mobile trailers or container housing. Electricity, gas, water and waste water provisions have to be made sure. (Cahill 2014; Alexander 2012)
In general, supply chains try to realize and optimize the four “R”s which are right product, right place, right time and right cost. Time and cost can be ignored in a locally and timely concentrated mine accident. The right product is more challenging as seen for example in the case of Lengede. In humanitarian logistics, so-called emergency item catalogues are an emerging trend to specify the specific parts or necessary units. However, too rigid specifications decrease the flexibility of the procurement operators. The right time is, in turn, depending on quality and quantity of the ordered product. Feedback loops can identify critical products like drilling tools to be replaced by more readily available types – preferably in advance of an incident. (Fenton et al. 2014)

The emerging supply chains require and cause much traffic. Traffic control is necessary as well as maintenance and fuel supply precautions (Alexander 2012). Besides equipment and supplies, Auf der Heide (1989) adds personnel and facilities to the critical resources within a disaster. A corresponding needs assessment includes a situation analysis and a resource analysis to identify the true demand for the supply chain. The security zones and checkpoints can then be used as a check-in area for incoming goods and persons – both professionals and volunteers.

5.2.9 Communication and Information

Information and its communication are the basis of coordinated disaster response. The demand for information is human and natural. The case studies have shown that both the communication between the participating rescue organizations as well as the communication to external parties of stakeholders is obligatory for emergency managers. Communication values the sorrows of the effected families and the needs of journalists. Furthermore, it is necessary to manage a multi-agency response mission. (Demiroz and Kapucu 2012; Doepel 1991)

Comfort et al. (2004) emphasize that cooperation without information is not feasible. Accordingly, Auf der Heide (1989) traces back coordination deficiencies to communication problems during disasters. From the technical site, inter-agency communication requires interoperability of communication equipment and channels as well as the underlying structure of reports or decision support systems (Comfort 2005). The different channels of
disaster communication have been compiled by Chen et al. (2007) and are depicted in the subsequent Figure 30:

Sensors (e.g. of the underground mine) as well as the responding teams contribute to situation reports from the site. The value of additional input of knowledge by experts has been stressed in the above analyses of this thesis. The two sources of information are processed and built the foundation for management decisions. These decisions together with compiled key information are then forwarded to the different stakeholders like rescue teams and media.

Auf der Heide (1989) discusses the most important steps of the above mentioned information management: The real disaster situation is continuously assessed and these assessments lead to selected countermeasures. These countermeasures require certain resources which have to be communicated with the logistics section. Competing countermeasures possibly require setting priorities in resource allocation. Finally, the delegation of responsibilities for the different actions is one more part of the communication of information.

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42 Heath 2001 states that receiving definite information or data from the site helps to reduce the early worst-case assumptions. Accordingly, a real-time comparison of planning and facts continuously increases efficiency during disaster response.
5.2.10 Control Centers and Posts

Disaster management needs infrastructural facilities during long-lasting missions. The case studies have shown some improvised headquarters and Quarantelli writes emergency operations centers in his requirements and instructions. Following the idea of coordinative control rather than military command, the corresponding facilities are named control centers and posts for the scope of this thesis.

Alexander (2012) distinguishes two types of facilities where command and control are conducted during disasters, which are local incident-command posts and a main emergency-operations center. The post is a small sub-unit of the center to extend command and control functions to the scene of the incident. Mobile trailers can be sufficient to coordinate the key operations like search and rescue. Despite its spatial separation it is still part of the organizational and jurisdictional structure of the overall management at the center. Resulting logistical challenges can be met if the post agrees with the aforementioned zones in the logistical system (see 5.2.1).

The main control center represents the physical realization of planned disaster management structures. This requires a room or structure which is sufficiently (and redundantly) connected to infrastructure regarding traffic and tele-communications. Large screens, projectors and tables are necessary to show plans and maps during discussions of disaster management boards. Suitably equipped committee rooms enable meetings of the leader with external experts or section leaders during decision-making. Also the control center itself as a central point of the communication and information network can be seen as a means of decision support. To meet the challenges of long-working shifts and fatigue (as discussed on p. 106), nutrition provisions and sleeping arrangements must further guarantee certain autonomy. Also the facilities for press conferences and media infrastructure (see 5.2.7) can be included into a control center; however a clear separation to management has to be kept. (Alexander 2012; Mendonça et al. 2001)

The mining industry already provides certain emergency management facilities – usually a single control room. If it is not a reserved room as provided by mine rescue stations, also mining engineering offices (respectively in surveying or ventilation departments) are seen as suitable to plan complex mine rescue missions (Ministry of Energy, Mines and Petroleum
Resources 2008). Graham and Eave (1995) provide a full organizational view on corresponding South African standards. However, most of the achievements in mining today put into focus short-term fire-related incidents.

5.3 Transfer to Mine Rescue

Equivalent to disaster definitions, long-lasting mine rescue missions can require multi-agency response, international aid and governmental involvement. Out of disaster management principles, especially continuous preparedness planning and response are important steps to cope with this thesis’ scenarios. During the response operations, the generic functions such as search and rescue, communication or logistics must be quickly established.

The preparedness planning process shall put into focus moderate size incidents. For the scenario of miners trapped underground a moderate size incident could be a group of four miners in a road-heading operation (Lehnen et al. 2015). Prepared plans should provide a framework which is suitable to let mine rescue management coordinate multi-agency response and cooperation. Full action plans can only be made during the mine accident itself because highly individual cases require flexible tactics and decisions.

ICS and CIMS are such accepted frameworks for disaster management. Their general organizational outlines are comparable though CIMS does without a separate financial section. That seems to be applicable with respect to mine rescue where time and cost should be ignored in the first place (see p. 111). Thus, the leaner structure of CIMS is preferred here. However, ICS provides some relevant principles:

A modular structure allows sub-sections to be removed or added where necessary, e.g. for drainage operations in all inundation-causes scenarios. Agencies stay jurisdictionally autonomous while they respect a lead agency for unified command. Each agency’s top leader can still participate in decision-making. This time-consuming procedure as well as the whole military command character is critiqued. However, reporting to single supervisors in a clear chain of command is crucial to keep an overview of the full rescue operation. The span of control of each supervisor is kept to a limit of three to seven sub-ordinates. Subsidiarity is frequently seen as a key principle in disaster management (see Table 14, p. 99).
As told above, CIMS provides a pre-defined structure which is adaptable to major mine rescue missions. In multi-agency response, control is conducted horizontally whereas each agency reserves the right for vertical command. This is crucial for mine rescue as well, for example to control the progress of several drilling rigs which are individually operated by their owners and approved teams. Such delegation of tasks also represents a criterion of Quarantelli’s for successful disaster management, as given in Table 13 (see p. 99).

The CIMS controller approves plans and is responsible for liaison and cooperation, both internal and external. Here he receives support by safety, information and liaison advisors which would be crucial positions in mine rescue as well. To include stakeholders like media is also important for the planning functions within CIMS. This could be the provision of mine plans by the engineering or surveying departments. To prevent conflicts and to keep a one-voice policy, the information officer should receive such information to publish it when suitable.

The operations section conducts the actual rescue and reports progress and risks. Flexible modules within the organizational structures must be assigned to the range of special capabilities like drilling and pumping conducted by sub-ordinate agencies. Corresponding to the earlier case studies, a separate CIMS section is responsible for important logistics aspects like transport, catering, communication, shelters and medical support.

Logistics has to meet both response and agent generated demands. First, the transport, and second the spare parts of crucial drilling equipment are examples which show how important logistics are during mine emergencies. An early as well as ongoing needs assessment is necessary to be in line with the individual requirements. Some demands can already be anticipated in the preparedness planning process. During response, security check-points help to register and control incoming traffic including a variety of volunteers and supplies which is an example phenomenon of disasters and major mine rescue missions.

Also the long duration challenges disaster and mine rescue logistics. Responders and families require shelters together with infrastructure like medical services, sanitation and transportation. Another example of disaster phenomena are emerging groups and changing organizational behavior. The affected companies’ own efforts like corporate mine rescue teams have
to be coordinated with external aid like drilling experts who might not be familiar with emergency response.

Being in line with the needs of long-lasting mine rescue missions must also include preparing a comprehensive list of stakeholders like media, authorities, families, and mine rescue experts in advance. Dramatic entrapments of miners underground leads to large media interest. Their demand for information and infrastructure has to be anticipated in preparedness planning. During response, one contact person must provide press releases and conferences. If possible, a combined tour for politicians and journalists should be conducted.

Although the trapped miners’ families have comparable needs for information and infrastructure, they must be strictly kept isolated from the journalists. Miners, who are not affected by entrapment should be informed but asked for discretion. They can be integrated into rescue operations as familiar guides for mine rescue teams from other mines which is a good way to permit own efforts they possibly offer.

As stated before, individual and dynamic mine rescue scenarios require sudden and improvised decisions. To coordinate personnel and resources during such unplanned, multi-agency response missions, intuitive and creative leaders need to have both knowledge and an insight into people and situations. Leadership has to provide strategy and vision without over-optimism. A small advisory team contributes to participative decisions and protects especially the managers within a small community as mining is. To physically support the leaders, shift plans need to guarantee sleep time and coordinated handover briefings.

Coordinative leadership still requires some central decision like for parallel or dominating rescue strategies. Such decision making possibly has to take place in a short time and with fragmentary data. As visualized on Figure 29 (p. 107), this thesis recommends a coordinated style for such decisions. They should be based on several pillars: External experts can provide valuable advice out of their specific fields like overpressure or psychology. Plans and procedures can facilitate decisions by anticipating risks and possible countermeasures. Intuition and flexibility are necessary for innovative and improvised actions for situations that have not been pre-planned.

Lessons learned and scientific evidence, as provided by this thesis, can support decision making as well. Thus, processing of information can be a crucial pillar for decisions.
Accordingly, valuable data regarding damaged infrastructure or occurring multiple hazards can be reported by underground sensors and mine rescue teams to mission control.

A main control center is necessary to centrally collect such information and coordinate multiple strategies and collaborative response. Communication and accommodation infrastructure are to be integrated. Mining engineering offices can be a suitable location to plan major mine rescue missions. In addition to a main center, disaster management further recommends de-central posts close to the incident’s sites. But because mine rescue missions are local incidents, the shaft or a drilling site possibly become a fixed point and, in opposite to natural disasters, external communication can be conducted in peripheral zones.
6 Developing the Mine Rescue Management Concept

The scenario definition of chapter 2 and the statistical evaluations of chapter 3 have identified the risk of long-lasting entrapments in future mining. Case study analyses (chapter 4) provide lessons from success stories and gaps to be filled by disaster management as worked out in chapter 5. As a final step, these works are now concentrated to create the Mine Rescue Management (MRM) concept.

The subsequent chapter 6.1 develops a definition of MRM by the use of three derived Lemmas. Afterwards, chapter 6.2 gives the key functions of MRM. They build the actual MRM concept and are structured by three sub-chapters: Planning steps in advance of an incident (6.2.1), the response mission as such (6.2.2), and an evaluation after each rescue (6.2.3) make a tripartite management concept.

6.1 Development of a Definition

The term of Mine Rescue Management (MRM) has not been defined yet. Long-lasting mine rescue missions bare new dimensions to mine rescue; and the approach of this thesis also provides new solutions and organizational standards for corresponding scenarios. In the following, three Lemmas represent the scope and the approach of this thesis and lead to the final definition of MRM.

Lemma 1: Mine Rescue Management covers long-lasting missions to rescue miners trapped underground.

Rescuing trapped miners is a rare and special task in the field of mine rescue. Large inundations or roof collapses are seldom and highly individual incidents. However, certain scenarios can cause long-lasting missions. Duration of several weeks or even months bares new dimensions like the different groups and interests of stakeholders or complex logistic networks. Such a major mission goes beyond the scope of “day-to-day” mine rescue. Here, the need for a comprehensive and wide-ranging MRM has been identified. Thus, MRM meets the challenges of long-lasting rescue missions for miners trapped underground.
Lemma 2: Mine Rescue Management is an evidence-based management concept.

The approach of this thesis to meet the challenges given in Lemma 1 is to provide scientific evidence in order to prepare a corresponding management concept. That increases preparedness for such incidents. Statistics and quantitative analysis of a mine rescue database helped to narrow down the scenarios of long-lasting entrapments. The subsequent case study analyses derived qualitative lessons to learn. Weaknesses or gaps of such past mine rescue missions are met by the implementation of disaster management principles.

These implementations and transfers make the MRM concept an evidence-based approach. As already introduced in chapter 5.2.6, Rousseau (2005) argues that “Evidence-based management [...] derives principles from research evidence and translates them into practices that solve organizational problems”. Corresponding to the identified needs and solutions, the MRM concept put into focus organizational or management issues:

Lemma 3: Mine Rescue Management comprises preparedness planning, response and evaluation.

MRM provides guidelines to prepare a best-possible response to a major mine rescue mission as defined in Lemma 1. As many organizational provisions as possible are to be made in advance to the incident and thus can be seen as preventive measures. However, the case studies have shown that certain issues and tactical decisions are situational. Here, MRM provides comprehensive guidelines and principles. Furthermore, the value of qualitative lessons learned has been proven. Hence, MRM includes systematic learning from new missions. Thus, a continuous improvement and change of the planning part is important.

The subsequent chapter 6.2 uses this trichotomy of Lemma 3 to structure the MRM concept. Altogether, the three Lemmas of long-lasting entrapments, scientific evidence and continuous response planning lead to the definition of MRM as derived in this thesis:

**Definition:** Mine Rescue Management is an evidence-based approach to prepare for, respond to, and learn from a long-lasting rescue of miners trapped underground.
6.2 Key Functions

Lemma 3 (see p. 120) introduced MRM’s trichotomy of planning, response and learning. The subsequent Figure 31 makes a projection of these three steps of MRM on the time scale of a major incident: Planning has to be conducted in advance of an incident and is preventive. In contrast, the response during the incident is reactive. The mine rescue mission is then followed by an afterwards evaluation.

![Figure 31: Key Functions of Mine Rescue Management](image)

Figure 31 also gives the structure for the subsequent sub-chapters. Chapter 6.2.1 represents all steps that can and should be planned in advance of a future incident. A framework including organizational structures and clear responsibilities increases the preparedness of a mining company for a major mine rescue mission. Planning must anticipate and show possible stakeholders, experts, suitable equipment and partners. Also location, infrastructure and duty cards for control centers are to be prepared by each mine operator.

The thesis has shown that preparedness planning is only feasible to a certain extend when it comes to highly individual and rare cases like long-lasting entrapments. Thus, chapter 6.2.2 provides general principles for the operational response. Basic strategies can be proposed regarding the different possible scenarios. Detailed tactics which react on specific circumstances must agree with the specific situation. They possibly rely to a certain amount on contingencies, intuition and leadership. Nevertheless, MRM includes approved standards and guidelines regarding operational steps to be conducted. Approved actions require satisfactory logistics and internal as well as external information channels.

As the third key function of the defined MRM trichotomy, chapter 6.2.3 comprises learning as the evaluative step after an incident. The evaluation of both organizational and operational mission success and failure has to lead to systematic lessons. These lessons are to be
implemented into a continuous improvement and progress of preparedness planning. Learnings have to be shared on inter-agency as well as international scale. Furthermore, lessons make new experts to be involved in future missions.

### 6.2.1 Planning

Planning takes place in advance of a future incident. Prepared plans have to provide a framework which meets the challenges and requirements of multi-agency and long-lasting missions (see 5.3). Such a structural framework or organigram shows clear roles and responsibilities which have to be staffed accordingly. In addition, the following remarks include the preparation of comprehensive stakeholder lists, anticipate technical planning, and recommend a pre-planned control center.

**Framework.** As derived in chapter 5, CIMS provides a suitable framework to manage multi-agency disasters. Its structure builds the basis for the modified MRM organigram. The subsequent Figure 32 shows the developed MRM structure:

![Figure 32: Mine Rescue Management Structure](image-url)
The organizational structure comprises flexible modules which can be extended or removed according to the specific needs or priorities of the current scenario and rescue strategy. Referring to CIMS, horizontal control and vertical command are included (see 5.3). Since the rescue of trapped miners is a technical challenge in the first place, it is recommendable to include an engineering advisory team around the central management of the rescue operation (see 4.3.2). This would represent the CIMS planning section. The two other key sections of logistics and operations can be adapted in MRM because they are also crucial to major mine rescue missions.

Roles Description.

Comparable to the CIMS controller, the MRM Coordinator (MRMC)\(^{43}\) approves plans that result from the decision team meetings. Furthermore, he or she coordinates liaison and cooperation within the MRM organization as well as with external stakeholders. Thus, the MRMC accounts for the Level 4 necessity of delegation as well as for the disaster management principles of leadership and decision-making which will be further described in the subsequent chapter 6.2.2. The MRMC is supported by four staff positions:

The Stakeholder Officer (SO) represents the equivalent Level 4 code and disaster management principle of caring for the needs of different groups of stakeholders. CIMS’ Information Officer has been renamed to pronounce that the SO only takes the responsibility for communication to external parties like families and media. This is in contrast to the Inter-Agency Officer (IO) who communicates internal information to the participating rescue agencies who provide external aid (another Level 4 code) to the mine rescue mission.

The Evaluation Officer (EO) and the Advisory Board (AB) are two new staff positions compared to CIMS. The AB allows for including external experts to the decision-making of the MRMC. The EO accounts for the MRM step of learning. By recording logs and receiving data from the different sections, he or she can cause systematic lessons learned. That allows the subsequent development of preventive measures (see equivalent Level 4 code) and establishing continuous improvement of the MRM concept (see 6.2.3).

\(^{43}\) Appendix 7 provides a table that shows differences and equivalents between CIMS and MRM. Furthermore, the abbreviations for MRM positions are repeated again (see also Table 16 on p. 126 for one more overview of the following abbreviations).
The first of the three main sections supporting the MRMC is controlled by the Planning Manager (PM). He or she provides strategic advice, mapping and shift plans. To do so, the PM is supported by four unit leaders. The Situation Unit Leader (STUL) monitors and predicts phenomena regarding the Level 4 code of natural events like outbursts or secondary in-rushes. Since such incidents are also the primary threats to the mine rescue teams, the STUL also accounts for their personal safety (replacing the Safety Advisor of CIMS).

The Information Unit Leader (IUL) prepares information material like maps and statistics supporting the IO and SO. The Administration Unit Leader (AUL) provides secretarial services and makes shift plans to make sure regular change-over of all positions. In the fourth planning unit, the Resources Unit Leader (ROUL) calculates demand and optimizes deployment of both equipment and personnel. Thus, the ROUL represents the planning part of the logistics. The importance of logistics is pronounced by the corresponding Level 4 code and the according disaster management principle in the previous chapters of this thesis.

The second and central section of MRM is the operations. The Operations Manager (OM) takes the responsibility for the resolution of the incident by applying cooperation and keeping the possible risks in mind. Four units are suitable to be in line with the generic duties of major mine rescue missions. The Search Unit Leader (SRUL) coordinates all technological and organizational tracking measures to locate the trapped miners. The second important application of the Level 4 code of technology is the inner rescue. Here, the Rescue Unit Leader (RUUL) takes account for drilling or pumping operations.

If pumping is not to release the trapped miners but to keep them alive, it is a countermeasure against the Level 4 phenomena of natural events. Also gas and rock mechanical issues are met by the Ground Control Unit Leader (GCUL). The fourth operations unit is coordinated by the Support Unit Leader (SPUL). His or her measures to support the trapped miners such as communication, nutrition and first aid are comprised by the according Level 4 code.

The third main section of MRM is logistics that represents the satisfaction of all response generated demands. The Logistics Manager (LM) takes the responsibility for the acquisition and transportation of equipment and the provision of infrastructure. Five units support his or her work. The Communications Unit Leader (CUL) installs equipment and maintains the
communication networks. Thus, the CUL is responsible for the technical part of the disaster management principle of communication and information.

The Shelter Unit Leader (SLUL) is responsible to provide infrastructure and food for the rescue teams, the control center, and the external stakeholders like the miners’ families. Thus, he or she replaces the two unit leaders of catering and facilities within CIMS. Next, the Ground Support Unit Leader (GSUL) accounts for traffic-related issues like transportation and fuel. In addition, he or she coordinates security and zoning work within MRM.

The Medical Unit Leader (MUL) provides expertise and support such as first aid for both the rescue personnel and the trapped miners. Finally, the Finance Unit Leader (FUL) takes the responsibility for the acquisition of the necessary material. His or her data are an exemplary input for the EO’s work. The subsequent chapter 6.2.2 will further show the corresponding duties and principles regarding the operational response as well as logistics.

Responsibilities. According to ICS, each agency within the operating network acts jurisdictionally independent. They operate self-determined while respecting and fulfilling the overall strategy and their specific rescue tasks. Although this thesis prefers the idea of coordination instead of command (see 5.2.4), the ICS principle of a clear chain of command is kept because each position in the organizational framework reports to one controlling unit. Also the span of control shall not be more than seven subordinates. That contributes to the key principle of subsidiarity (see 5.3).

The assignment of the different MRM positions with certain persons or agencies is shown in matrix shape in the subsequent Table 16. The matrix has to be seen as a recommended delegation of roles and responsibilities. The central column distinguishes internal (corporate) personnel and external agencies which will be further discussed below.
### Table 16: Mine Rescue Management Staffing Matrix

<table>
<thead>
<tr>
<th>MRM Position</th>
<th>Agency</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRMC</td>
<td>MRM Coordinator</td>
<td>external, internal</td>
</tr>
<tr>
<td>EO</td>
<td>Evaluation Officer</td>
<td>external</td>
</tr>
<tr>
<td>SO</td>
<td>Stakeholder Officer</td>
<td>external, internal</td>
</tr>
<tr>
<td>IO</td>
<td>Inter-Agency Officer</td>
<td>internal</td>
</tr>
<tr>
<td>AB</td>
<td>Advisory Board</td>
<td>external, internal</td>
</tr>
<tr>
<td>PM</td>
<td>Planning Manager</td>
<td>external</td>
</tr>
<tr>
<td>STUL</td>
<td>Situation Unit Leader</td>
<td>internal</td>
</tr>
<tr>
<td>IUL</td>
<td>Information Unit Leader</td>
<td>internal</td>
</tr>
<tr>
<td>AUL</td>
<td>Administration Unit Leader</td>
<td>internal</td>
</tr>
<tr>
<td>ROUL</td>
<td>Resources Unit Leader</td>
<td>external</td>
</tr>
<tr>
<td>OM</td>
<td>Operations Manager</td>
<td>external, internal</td>
</tr>
<tr>
<td>SRUL</td>
<td>Search Unit Leader</td>
<td>external, internal</td>
</tr>
<tr>
<td>SPUL</td>
<td>Support Unit Leader</td>
<td>external</td>
</tr>
<tr>
<td>RUUL</td>
<td>Rescue Unit Leader</td>
<td>external</td>
</tr>
<tr>
<td>GCUL</td>
<td>Ground Control Unit Leader</td>
<td>internal</td>
</tr>
<tr>
<td>LM</td>
<td>Logistics Manager</td>
<td>internal</td>
</tr>
<tr>
<td>CUL</td>
<td>Communications Unit Leader</td>
<td>external</td>
</tr>
<tr>
<td>SLUL</td>
<td>Shelter Unit Leader</td>
<td>external</td>
</tr>
<tr>
<td>GSUL</td>
<td>Ground Support Unit Leader</td>
<td>external</td>
</tr>
<tr>
<td>MUL</td>
<td>Medical Unit Leader</td>
<td>external</td>
</tr>
<tr>
<td>FUL</td>
<td>Finance Unit Leader</td>
<td>internal</td>
</tr>
</tbody>
</table>

The staffing of some positions depends to a certain extend on the size of the affected company – for example, a spokesperson to the media must be an approved person (as described in 5.2.7). If a small mining company cannot provide such a competence, he or she should be an external specialist. Other positions must agree with the scenario and could be even removed, if not necessary. Nevertheless, such a matrix must be individually prepared by each mine operator in advance of an incident.
The question of internal and external MRM personnel not only depends on the size of the affected company. Due to the cause of an incident and potential legal or corporate investigations, an internal mine manager might not independently decide. Installing external MRM personnel makes sure clear priorities for rescue and non-emotional decisions. Special trainings also guarantee his or her ability to coordinate unique, unplanned multi-agency response. Nevertheless, internal representatives know the specific circumstances and geology of “their” underground mine best. Thus, they should be included in the decision-making team of an external MRMC.

Furthermore, potential replacement or deputy persons have to be named. To prevent sleep deprivation and exhaustion of key persons, shift plans and replacing persons are necessary for each critical position. Coordinated handover briefings are necessary before and after each shift (see 5.3). The AUL must follow prepared changeover systems as provided in Appendix 6.44

**Stakeholders.** Besides a list of persons to fill the above given MRM structure, also a list of possible stakeholders of a large incident has to be anticipated and prepared. This thesis has shown that journalists, politicians, public authorities, families, mine rescue teams, external experts and volunteers are typical stakeholders of long-lasting mine rescue missions. Chao (2008) further recommends including legal representatives, property owners and mining company officials to the list.

However, the predominant emergent groups out of this variety of stakeholders are media, families and politicians. They require considerable infrastructure, support and information (Lesson 9 in chapter 4.3.3). The preparation of a comprehensive list of all possible stakeholders is an important step in MRM planning. This includes anticipating their needs for infrastructure and information.

Major mine rescue missions possibly require including multiple agencies, international aid and governmental influence into the organizational framework. Also corporate miners who are willed to support the rescue efforts for their trapped colleagues can be included as

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44 Here, the four groups A to D correspond to the four MRM groups of Control (and staff), Logistics, Operations, and Planning.
familiar guides at the site (or even underground) to support the external rescue teams and specialists (see 5.3).

An efficient blending of established organization like the mining companies’ rescue teams and emergent groups like external rescue experts is crucial to mission success. For example, cases of complex inundation require diving or navy specialists to be included into the development of safe rescue strategies under overpressure. Psychologists and physicians are necessary both for support of the trapped miners underground and the care of their families on surface (see 4.3.2).

**Technical Planning.** Preparedness planning for MRM not only comprises organizational issues. Also technological aspects for a major rescue mission can be anticipated. Central mining institutions and central rescue stations as of MSHA in the U.S. provide special equipment and experts for specific tasks like seismic tracking or decompressing.

The mining company should also have suitable emergency contacts prepared including drilling experts. The same applies to allow ordering special drilling equipment fast which fits the geology and maximum depth of the underground mine (see 4.3.2). Suitable equipment selection comprises both own and foreign machinery. Besides tracking and drilling equipment, also other machinery like generators, pumps or bulldozers are possibly necessary.

Furthermore, up-to-date mine maps (also from mined-out areas) have to be available. With respect to long-lasting entrapments, especially the dynamic road-heading operations are of high relevance. For more stable constructions like permanent rescue chambers special drilling plans and sites on surface can even be prepared in advance. This starts with agreements with adjacent land-owners to receive non-bureaucratic permissions to go across properties if an emergency occurs.

**Control Center.** Improvised headquarters are crucial to collect and provide internal as well as external communication and information during MRM. Thus, they are an important component of MRM’s collaborative response strategies. The necessary infrastructure can be installed in preparation of an incident. Regarding the technical infrastructure, mining engineering offices of the affected underground mine could be suitable (see 5.3).
Control centers provide management infrastructure such as communication systems as well as basic accommodation. Within the MRM structure, the GSUL becomes responsible for maintaining and extending the center as necessary. Although control centers are the place to agree communication, the real transfer of information to the outside – such as press conferences – can be conducted in a different location respecting the zoning principle which is going to be addressed in the logistics section of the subsequent chapter 6.2.2.

### 6.2.2 Response

This thesis has shown that preparedness planning can only cover a certain part of highly individual and rare cases like long-lasting entrapments. Detailed response plans must agree with the complex and unique mine accident. Thus, this chapter provides principles and standards that still allow creating flexible tactics and making innovative decisions during the specific response.

Thus, the following remarks build a mosaic that increases efficiency and the chance for success during the rescue of trapped miners. Therefore, this chapter provides guidelines on basic strategies, the operational response as the individual tactic, the decision-making and leadership procedure of the management, and the main section of logistics with its related fields.

**Basic Strategies.** The basic strategies regarding the different possible scenarios all compile the generic operations of search, support, rescue, and ground control. The PM has to take account of the logical time series which underlie each rescue mission: Search operations have to succeed before support and rescue efforts can be started. On the other hand, ground control measures are necessary during all phases from the first day on.

The time of search by the surface teams is equal a life-critical and thus time-critical fight for physical survival underground. The timeframe after successful search and until the final rescue allows for external support but also causes a psychologically stressing wait for escaping the entrapment and the confinement within a strained group (see 4.3.2). Major mine rescue missions might be forced into different intervals of waiting times which are possibly necessary to
• Register signs of survival,
• Prepare drilling sites,
• Repair crucial equipment,
• Reach a critical water level by drainage or pumping,
• Rest in decompression chambers.

Parallelization and redundancy have been identified as crucial principals for the technological operations in a rescue mission: Surveying and collar preparations for subsequent drilling sites can be conducted while the drilling equipment as such is still transported to the mine. When drilling takes place, dewatering measures can be conducted parallel as well. Thus, parallelization accelerates the necessary sequences within the life-critical project (Lesson 3 in chapter 4.3.3). With respect to the earlier given time-frames, drilling and pumping operations can become life-critical. Such machine applications should always be conducted redundantly (Lesson 4).

The subsequent Figure 33 shows in the top part a simplified flowchart of the basic MRM operations. In the lower part, examples for each type of operation are given. They are going to be described in more detail afterwards.
Operations. Search, support, ground control, and rescue are generic functions of all rescue missions. Their quick realization is crucial. The same applies for response generated demands like information and logistics which are going to be addressed at the end of this chapter. Approved standards and guidelines regarding the operational steps could be separately written in a “hot book”. Referring to Schneid and Collins (2001), emergency plans shall start with a red (hot) section for the most crucial response steps. They would be followed by a blue “cold book” containing preventive measures like evacuation plans or detailed procedures for logistics and other support functions.

In the MRM concept, the OM takes the responsibility for the four types of operations, respectively overviewed by four Unit Leaders: Each rescue mission, where the location of trapped miners is unknown, has to start with search operations. Inclining sealed drifts can provide survivable locations above water level after major inundations. Considering mine plans for such criteria can be the starting point for successful search operations (see 4.3.2). Also the matching of shift and mine plans can contribute to a pre-assessment before technical search applications like small-diameter drilling start their concise work. Other indicators of life can be seismic tapping signals or air bubbles and pressure leaks resulting from premeditatedly and intentionally broken compressed air lines.

Thus, the SRUL manages a variety of parallel search options. The quantitative analysis of this thesis’ database further shows that human beings can sustain enormous and unexpected time-frames of un-supported entrapments. The mine accident of Xinqiao (China 2009) can be seen as the “world-record” of 25 days of survival without external supplies in an underground mine. Thus, search operations and hope should not be given up until the proof of death or survival of each missing miner.

Successful small-diameter drill holes out of the search process become key lifelines to support the trapped miners. Water, nutrition, and first aid are the most important physical supports (see 4.3.2). The SPUL (in cooperation with the MUL) must not limit these support operations on continuous supply. Underground emergency provisions have to be built up as soon as possible to allow the bypass of technical problems or even the loss of a drill-hole.

Having identified the location of the trapped miners, more small-diameter drillings can quickly open new channels for communication and other support which can be
psychologically important. Positive group dynamics then facilitate the interaction between the trapped miners and surface control. Possible support from the trapped miners to the rescue operations, e.g. by moving drilling cuttings, must not be underestimated.

Depending on the scenario, the injection of fresh air might be necessary to provide oxygen in small and sealed confinements. Also the resulting effect of overpressure can be necessary to repress hazardous gases or increasing water levels. In any case, it is recommended to keep the underground mines’ air compressors running until the final rescue of trapped miners. And even before the discovery of trapped miners, air injections can significantly increase their chance of survival (Lesson 6 in chapter 4.3.3).

A successful search for the location of the trapped miners initiates the rescue operations to release them. Again, different approaches are possible and should be applied by the RUUL parallel and redundantly, when feasible. If mine rescue teams still have access to go underground, they can start drilling or other “mining” steps underground as close to the trapped miners as possible. These procedures include re-driving or re-opening collapsed drifts or developing even new ones to rescue miners in an inundated but still open mine. As the worst case scenario, large-diameter drilling from surface has to be conducted if all mine openings are impassable.

As visualized in Figure 33, ground control is one more field of work that must start immediately after the notification of an incident. The GCUL conducts and supervises such operations in consultation with the STUL. Pumping strategies can be developed to protect trapped miners. As described in the case studies before, further small-diameter drill holes can be used for drainage or to insert roof support. Besides the stabilization of rock, also the re-establishment of ventilation is a key issue when dealing with the identified Level 4 code of natural events.

Natural events and the according technology application are two of the generic functions which have been identified by the coding procedure in each of the single case studies (see 4.3.1). The specific circumstances and the specified tactics are highly individual and agent-generated. Thus, they can change considerably from mission to mission. The STUL has to plan detailed tactics to meet the specific circumstances of the actual incident. This could be the presence of overpressure or the absence of fresh air to the trapped miners. More
examples for natural threats that can occur even after the initial event are methane outbursts and secondary collapses of rock or further inrushes of water.

Leadership. Preparedness planning as well as operational response is kept to a limit by the individual and dynamic behavior of a long-lasting entrapment and the specific underground conditions. That requires sudden and improvised decisions which possibly rely to a certain amount on contingencies and intuition. This defines the need for leadership which has to make specific tactics and to provide respectable vision (see 5.3).

A coordinative style of leadership is recommended for MRM. Creative leaders and especially the MRMC need knowledge as well as insight into people and situations to be able to coordinate multi-agency response. That allows developing complex and innovative strategies. But still, coordinative leadership comes to situations where central decisions have to be made. They can be pressing and also based on fragmentary data.

Figure 29 (see p. 107) already showed the decision support concept as developed for MRM. Intuition, plans and experts are different pillars that can be useful decision support. A small advisory team (AB), as recommended in chapter 6.2.1, contributes to participative decisions. The involvement of external experts as necessary in specific fields like medicine or drilling technology must be achieved as early as possible (Lesson 8 in chapter 4.3.3).

According to ICS, the different section or unit leaders of the different autonomous agencies should be able to participate in the decision-making procedure when their specific competences are necessary. However, language and qualification barriers of external aid as well as a missing overall coordination can hamper efficient rescue and thus require strict leadership (see 4.3.2).

Experience and evidence as further pillars for decision support have to be communicated reliably and sustainably. This is going to be given in the subsequent chapter 6.2.3. Data (or information) even requires a real-time communication during the response itself and leads to the demand for information systems during disasters or major mine rescue missions.

Logistics. The progress of the rescue action itself causes response-generated demands (see 4.3.1). Logistics functions such as the supply of rescue teams or families can be comparable and common to different missions. Thus, they can be planned
satisfactorily in advance. However, logistics are mentioned in this response-related chapter because of their active character.

The necessary rescue equipment and experts are of first priority to the emerging logistics. This includes the initial transport of equipment and the subsequent provision of spare parts. An ongoing needs assessment has to identify (responsibility of the ROUL) and meet (LM with the support of the FUL) the requirements of the rescue teams. However, parts of it can be anticipated in the planning process of MRM, like an equipment checklist.

Traffic control can be delegated to public authorities like police, fire fighters and army. This also includes security checkpoints to realize and seal certain zones which are going to be specified below. Such check-points can also be used for check-in registration and control of incoming goods of the logistics system (see 5.3). These issues are coordinated by the GSUL.

Installation and supply of shelters can be supported by Red Cross or comparable associations and in cooperation with nearby hotels and restaurants. Physical and psychological support for the families on surface is important. Maintaining a stable psyche allows providing psychological support by the miners’ families to the underground as soon as communication channels are established. Besides the well-being of rescuers and trapped miners, the MUL must also guarantee for the medication of burdened families.

However, the technical rescue as the core of the whole mission does not depend on the emergent groups of families, politicians, and media. Thus, a clear spatial separation has to be achieved by sealed zones (see 4.3.2) which are another responsibility of the GSUL. Each zone, managed by the SLUL, needs to provide the required infrastructure (like shelter) for the specific group of stakeholders.

The subsequent Figure 34 shows a possible zoning at a mine site. Fences and security check-ins protect the different zones. Also the assigned traffic or road accesses must be moved apart as far away from the mine as possible. Rescue equipment and personnel need their own road for important transports. Thus, the stakeholders’ traffic should be directed to different tracks. Within the stakeholders’ zone, families of the trapped miners must be strictly isolated from journalists. As a central place of information and coordination, the control center should have protected access to all the different zones:
6. DEVELOPING THE MINE RESCUE MANAGEMENT CONCEPT

As another task of logistics, the CUL has to install and maintain information channels to the internal and external agencies of the rescue mission. The earlier mentioned separation of emergent groups and the core rescue operations further applies on the according organizational scale: The information flows clearly have to distinguish internal and external contents and receivers. Within the MRM organization, the IUL provides all kind of information and data. For the distribution, the IO organizes internal supply whereas the SO coordinates the information of the different stakeholders.

6.2.3 Learning

Learning as the evaluative step after an incident is the third step of the tripartite MRM concept following planning and response. However learning already starts during the response itself: The EO, installed to this end, collects data and initiates the evaluation. That comprises organizational and operational aspects of the rescue mission. Both successes and failures have to be regarded. Also the role of preventive measures can be evaluated posing questions like

- Which roles played previously installed public response standards and capacities?
- Would rescue chambers have helped or did they actually help?

For example, Lesson 10 in chapter 4.3.3 concludes that emergency provisions including drinking water and communication technology would be a powerful support in all long dead-end drifts of an underground mine. Thus, this would be a potential future application to
allow the support of miners trapped underground without one connection to the surface. The qualitative case study approach of this thesis has shown a possible procedure of creating **systematic lessons learned**.

Also the database of past rescue missions can be applied as an evaluation tool because it provides poor and strong benchmarks of comparable scenarios. Validated lessons are then to be implemented into a **continuous improvement**. That allows for constant progress of the preparedness planning process. The subsequent Figure 35 symbolizes that lessons can be learned from the response and that they are subject to a continuous revision and improvement of the plans and procedures:

![Figure 35: Systematic Learning and Continuous Improvement in MRM](image)

Besides that inner-MRM learning cycle, lessons have to be **shared** also on an inter-agency and international scale. The according publication of facts and figures can be one more application of a database of major mine rescue missions. Associations like the IMRB (see p. 5) or a potential European pendant could provide a platform for the exchange of experiences and lessons. This can also lead to training and provision of MRMCs by such central bodies.

More generally, the involved specialists of a rescue mission can provide their experiences as external **experts** within future missions – as incorporated by the AB in the MRM structure. According databases of experts including their specialties and experiences can be installed referring to certain types of scenarios.

An even other application of the lessons learned in an incident is to provide success stories to other miners trapped underground to increase their confidence and hope, as discussed in chapter 4.3.2.
7 Conclusion

To conclude this thesis, the subsequent chapter 7.1 will provide a discussion. This discussion will address issues like relevance of work, possible limitations, and alternative interpretations. Afterwards, chapter 7.2 will show perspectives of the prepared work. That addresses implication and application opportunities as well as recommendations for future research.

7.1 Discussion

The goal of this thesis was to develop a concept to prepare the management of a major mine rescue mission. The focus scenario for such a mission was a long-lasting entrapment of miners underground. The resulting Mine Rescue Management (MRM) concept should be based on two central pillars. These were case study analyses of past missions on the one hand and a transfer of selected disaster management principles on the other hand.

Such long-lasting entrapments can be seen as rare scenarios within mine rescue. For usual missions like minor equipment fires or gas detection, there are both corporate and governmental guidelines and procedures. Thus, this thesis develops standards for rare and individual mine rescue missions. However, the database developed in chapter 3 confirms the relevance of the conducted research. Long-lasting entrapments still occur in the 21st century. Incidents can be found throughout the different commodities and mine layouts of underground mining.

Nowadays mine rescue faces a debate of whether rescue chambers are a suitable measure to replace a second means of escape or even high-capacity self-rescuers. Chambers can also give a false sense of safety and fatally influence the decision whether to evacuate the mine or to proceed to a refuge chamber during mine fires. Oxygen deficiency can make chambers with limited air supply a deadly trap and a self-escape should be preferred under most circumstances.

Refuge chambers are made for short-term stays during the escape out of an underground mine. In contrast, rescue chambers are designed to provide a safe haven when escape is not possible or necessary. There, the miners would wait under oxygen supply for an aided rescue by mine rescue teams. (Lehnen et al. 2015, p. 236)
7. Conclusion

While such scenarios of fire and hazardous gases have been excluded from the scope of this thesis (as derived in chapter 2), chambers can be an innovative approach to provide a preventive or life-supporting measure for entrapment scenarios. Lehnen et al. (2015) discussed a re-design of today’s mobile rescue chambers to allow their application in dead-ends like development drifts.

Lehnen et al. (2015) came to the conclusion that slim chambers may not change regular mine development work and that sufficient water and nutrition could be easily provided. With respect to the case studies done in chapter 4 of this thesis, the cases of San José, Lengede (group of three miners) and Lassing also showed the life-supporting effect of emergency provisions or safe locations underground. In the chaotic and extreme cases of Beaconsfield and Lengede (group of eleven miners) a rescue chamber may not have been reachable because of the fast development of the initial events.

When compared to other single incident reports, the thesis’ case studies come to comparable results. However, each single case study is more comprehensive as showed by the coding method. By putting into focus several heterogeneous aspects of rescue missions, shortcomings of studies which were only dedicated to selected aspects like drilling technology or psychology have been overcome.

Limitations of the conducted case study analysis can be seen in the exclusion of detailed root causes. Also unsuccessful mine rescue missions like the fatal accidents of Sago (USA 2006) or Pike River (New Zealand 2010) were not subject to the database. However, Lassing includes sad examples of bad emergency management procedure and together with best practice as of San José provides valuable lessons which led to the MRM concept.

The scientific methods of triangulation (of sources) and systematic coding (of phenomena) guarantee a high objectivity of the interpretations. However, still your weighing of factors influences the coding procedure or has possibly caused a subliminal preference of selected references or codes. But the general results, however, lead to the interpretation that surface management has a notable influence on mission success and that management concepts and organization provide a high potential for improved preparedness.

An emphasized role of luck can possibly be an alternative interpretation of the shown cases. And one could also say that during major mine emergencies spontaneous aid and innovative
ideas will always lead to meeting the individual challenge without professional preparedness. Also the conducted coding includes luck and “miracles”. But this thesis further puts force into the potential of systematic learning of such success factors. The same applies for the power of international aid which could still be improved by prepared networks and shared management systems and standards.

Generally speaking, the transfer of social science methods to mining engineering has provided important results which go beyond the value of single incident reports. Building on that, the following disaster management studies showed large potential for improvement of safety and preparedness in the mining industry and mine rescue in particular:

For example the working over of decision support systems meets a global challenge and one more debate within the mine rescue community: The Pike River mine disaster and also the killed rescue teams of Lassing or the second collapse in San José uncovered an important need for research. The life-critical decision whether to allow a re-entry of mine rescue teams into an damaged underground mine (see for example Nugent et al. (2010)) requires joint and fast decisions which could be supported by the decision making model developed in Figure 29 (see p. 107).

Also a broader view on the current practical challenges and changes in mine rescue gives clear parallels to this thesis’ work and underlines the relevance of the developed MRM concept: In a stakeholder meeting, the Mine Safety and Health Administration (MSHA) (2012, p. 10) mentions, besides others, clear management related challenges within U.S. mine rescue: So-called “Command Center Operations” currently require improved decision-making, information systems and stakeholder care (especially for affected miners families).

In Germany, the mine rescue guidelines were reviewed in 2014. Roof collapse and major water inflow are now included in the list of possible duties for mine rescue teams. Also the application of refuge chambers is discussed. Furthermore, issues such as the obligation to confidentiality for team members and the need to prepare long-lasting missions shows interesting parallels to this thesis’ work on management issues and shows a possible application of MRM and again the relevance of this work.
7.2 Perspective

The discussion has shown a general relevance of the MRM approach. Current debates and changes in international mine rescue give a chance of possible application of this thesis’ concepts. The preparedness of long-lasting mine rescue missions has to be seen as an overall need for improvements on corporate, national and international levels. The scenario of miners trapped underground deserves increased awareness in the field of occupational mine health and safety.

Thus, both technical and organizational preventive measures regarding the given scenarios have to be considered. This can be a slim rescue chamber as discussed by Lehnen et al. (2015). For the case of large inundations, inclined parts (especially dead-ends) could become safe havens for retreat and should be signed as such – comparable to hills in Tsunami endangered areas. For the rescue mission, individual preparedness is required from each underground mine operator. Suitable rescue technology taking into account the geological situation or pre-assigned MRM roles as recommended by Table 16 (see p. 126) are examples of specifically necessary preventive measures.

Besides corporate preparedness, also international cooperation must be fostered. The case studies have shown the potential of mutual aid across borders. With respect to European mine rescue (see 1.1), the different national organizations provide a comparable hidden potential of partnerships. A real European mine rescue would allow broad capacities and shared know-how. Based on institutionalized mutual aid agreements, the single mine operator would get a cost-efficient preparedness for Low-Probability, High-Consequence (LP-HC, see p. 18) events. An according centralized European Mine Rescue Platform (EMRP) could then train and provide a professional Mine Rescue Management Coordinator (MRMC, see p. 123).

Thus, an application of MRM bears the chance of synergetic effects for the European mining industry. By cooperation and shared standards, only a management structure without major investments would be required. In bringing MRM to the mining community, universities could play a mediating role. Martens et al. (2012) have already discussed such a role of academia with respect to research funding and mineral policies.
Also the research around this thesis has been publicly funded: The i²Mine project is a European Framework Program 7 project (Grant Agreement Number: NMP2-LA-2011-280855). Here, my sub-task “deep mine rescue” became an integrative part during the development of “Innovative Technologies and Concepts for the Intelligent Deep Mine of the Future”. Need for research has been identified in technological fields of mine rescue at great depths.

Further research, both within technical and management communities, is recommended. Regarding the applied case study approach, it would be interesting to see analysis of bad practice and fatal accidents. Furthermore, interviews could provide different valuable sources besides reports and other written documents which have been analyzed within the scope of this thesis.

The developed MRM is a basic concept that invites future extensions based on further developments in mine rescue, emergency management and lessons learned. Thus, MRM is open for new experiences, trends and requirements out of the mine rescue community. Furthermore, an application of MRM in other types of disasters would be interesting. An application in man-made or natural disasters would give the chance to re-transfer mine rescue know-how and approved standards to the well-respected discipline of disaster management.
8 Summary

Underground mines are facing the challenge of increasing depth. At the same time, safe and economic domestic mining activities have to be seen as a crucial pillar of European mineral raw materials supply. Transferring great depths to the mine rescue scenario of miners trapped underground leads to long-lasting missions of unknown dimensions. This thesis tried to increase the preparedness for the surface management of such rare and extreme incidents by developing a Mine Rescue Management (MRM) concept.

An introductory analysis of European mine rescue showed important differences within the countries’ legal frameworks and organizational approaches. National regulations and highly individual organizational structures dominate compared to a few European standards. While some bilateral cooperation has grown over years, there is no European mine rescue as such. There are strong but heterogeneous capacities but they cannot be effectively shared by the European mining industry so far.

International research in mine rescue mainly goes for the development or improvement of technological equipment for response teams. The management of mine rescue missions is more based on experiences and training. The evaluation of major mine accidents is dedicated to root-causes of single incidents. International or multi-aspect or multi-case analyses can hardly be found. Also a comprehensive database of major mine rescue missions has been identified as a gap in today’s mine rescue research.

During this thesis’ approach a database has been developed to meet the identified challenges and needs for research. A quantitative analysis led to promising cases which became subject to single and multiple case studies. Remaining gaps were then filled by transferred disaster management principles. Both the lessons of qualitative case studies as well as best practice of civil disaster management became satisfactory pillars for the final MRM concept.

Fire, rockfalls, hazardous gases, and inundations have been identified by a literature review as well as by an own international survey as primary hazards in underground mining. Under certain circumstances, they can lead to the focus scenario of long-lasting entrapments of
miners underground. Taking both the potential location of miners underground and their specific depth into account, a developed classification system showed that mainly major rockfall and inundations can trap miners in dead-ends of a mine.

When no self-escape is possible anymore, such a scenario requires a long-lasting rescue mission at great depths. Since only dead-ends hold the risk for such an extreme case, modern mine layouts have been evaluated accordingly. Here, especially road-heading operations can be found in all underground mine development works. Long distances to vertical and horizontal neighboring openings or surface can result which leads again to an increasing complexity for rescue missions at great depths. Furthermore, sublevels and access drifts of certain hard rock operations show comparable dead-end properties.

In order to validate the potential risk of long-lasting entrapments, a database of past major mine rescue missions has been compiled. The database only includes long-lasting mine rescue missions of miners trapped alive in rather modern operations. The resulting data collection identified as many corresponding cases as possible and also aimed to collect as much information for every mine rescue missions as possible. Documentations were the primary type of referred sources which were triangulated whenever possible.

Altogether, 56 cases have been recorded. The database itself is based on MS-Excel to allow statistical evaluations. Besides quantitative and binary data also short qualitative information has been put in certain parts of the spreadsheets. All original text passages of the referred documentations have been kept in separate MS Word files.

On the time scale, the quantitative analysis of the database did not show a clear trend but the relevance of the conducted research still became obvious: The 21st century has already faced more long-lasting entrapments than the entire second half of the 20th century. In contrast to personal intentions, there is no clear correlation between depth and duration of according rescue missions. This is because of the high individuality of the different cases, especially with respect to rockfall scenarios.

The earlier scenario selection of major rockfall and inundations has been confirmed by the quantitative analysis. Furthermore, some extrapolation, e.g. of real drilling rates, allow
careful estimations for great depths. Durations of several months have to be expected and thus would require according management structures. Furthermore, the identified individuality of cases gave a good reason for appending detailed single case analyses.

**Case study** research provided the methodology for the careful analysis of selected mine rescue missions. The thesis mainly followed the principles of Yin and Creswell. A 4-Level coding procedure after Hahn was then the primary qualitative instrument in evaluating the single cases. San José, Wangjialing, Beaconsfield, Quecreek, Lassing, and Lengede have been selected as six cases to be studied in detail.

Looking for factors of success and other lessons to learn, the overall coding provided systematic and comparable structures for all case studies. The nine final Level 4 codes turned out to be Case Description, Delegation, External Aid, Logistics, Natural Events, Preventive Measures, Stakeholders, Support, and Technology. With their aid, hundreds of reference data could be systematically compiled and compared for each single case study both graphically and written:

The *San José* copper-gold mine collapsed in 2010 in a remote area of Chile’s Atacama region. 33 miners were trapped because of major rockfall for a record duration of 69 days. San José is maybe the most famous mine rescue mission in recent history and achieved high political relevance combined with global media presence. From the psychological perspective, it was interesting to see group phenomena which took place in a relatively large open void of drifts underground including a rescue chamber and scarce supplies. With respect to technology, San José showed a large depth of 700 m and a considerably high number of 13 surface drilling operations in total which could be rated as today’s best available equipment.

The inundation of the *Wangjialing* coal mine in 2010 represented a recent Chinese mission with relatively high availability of data. The 115 survivors have been accounted for the second-highest number of rescued miners out of one mission within the whole database. The third single case study was *Beaconsfield* 2006 as the only case identified in the mining country of Australia. Two miners were trapped at 925 m for 14 days. They could hardly move in a small telehandler which enabled their survival in collapsed rock. Careful underground drilling allowed their supply and rescue.
Quecreek 2002 was the last U.S. incident fitting the scope of this thesis. Without a supply of fresh air to the trapped miners it is an extreme case. Nine miners survived in a void of about 90 m³. The diversified rescue strategy comprised both drilling and pumping operations with the support of considerable external aid. Furthermore, Quecreek allowed evaluating American MSHA standards and successful stakeholder management.

In Lassing, Austria 1998, one miner survived for 9.5 days without external support. Nevertheless, Lassing, as the second last incident in Europe, globally stands for an example of unsatisfactory mine rescue management. Secondary inrushes killed mine rescue teams underground and unclear leadership structures hampered early professional aid and suitable stakeholder management. Also surface infrastructure was severely damaged by the inundation.

The German Lengede iron ore mine flooded in 1963. Two different groups of miners were trapped for 8 and 14 days and were rescued independently from each other and under very different conditions. Innovative approaches such as pressure chambers, external drilling specialists or the Dahlbusch-bomb (see p. 30) set standards for subsequent incidents worldwide. But also luck had significant influence on the success of the famous rescue mission.

The six single case studies’ results have then been put together by a multiple case study analysis. A first cross-case analysis identified Case Description, Natural Events, Preventive Measures, and Technology as generic functions within each single case. The aspect-oriented analysis then showed that survivable locations of the affected mine shall be pre-assessed before starting time-consuming drilling operations. All technical application should underlie a fundamental principle of both parallelization and redundancy.

Further lessons learned out of the multiple case studies were the life-saving potential of compressed air systems and air injections. With respect to management, an early integration of external experts is as crucial as the ministration of emergent groups like media, politicians, and families. The comprehensive list of ten lessons provides a framework that increases the chance for success in the regarded rare and individual scenarios. These lessons became subsequently subject to integration into the final MRM concept.
Besides such lessons, also best practice out of disaster management should be transferred into the MRM concept. Disaster management has to be seen as an independent discipline of research. Especially multi-organizational and international disaster response is of relevance to the identified needs during major mine rescue missions. The focus has been put into preparedness and response principles like search and rescue but also support functions like communications or logistics. Altogether ten principles, as given by the leading disaster management researcher Quarantelli, have been transferred to the needs (or gaps) identified by the case studies.

Long duration and the presence of multiple hazards, capacities, and agencies are interesting parallels between civil and mining disaster phenomena. Emerging groups have to be coordinated and damaged infrastructure can hamper efficient response. Thus, previously preparedness planning plays a crucial role in meeting challenges of multi-agency response or emergency logistics. Nevertheless, only a framework can be anticipated which still needs flexibility during the response mission.

The ICS provides an organizational framework including operations, logistics, planning and finances during disaster management. These modular functions are subject to a clear chain of command and limited span of control while different agencies stay autonomous. In contrast, the CIMS is a different organizational structure which highlights its coordinating (rather than military command) character. Its sub-functions are however comparable to ICS.

Independent from the management style, a certain quantity of leadership is necessary during disasters. The coordinative approach led to the concept of evidence-based leadership. Advisory teams and replacement arrangements are important for complex, long-term missions. Accordingly, decision making follows a comparable approach. It has been recommended to include advisors, information, procedures, intuition and evidence in preparing key decisions.

Stakeholder management has been identified as another crucial part of both the mine rescue case studies and in general disaster management. Relevant groups such as media, families and politicians have been identified. They cause a considerable demand for information and infrastructure which has to be integrated into resource and communication plans. Although their basic needs are comparable, a clear separation of certain groups is necessary.
This has notable influence on the logistics of disaster management. Besides supply of key rescue technology and personnel, also shelters, traffic management and communication infrastructure are necessary for helpers as well as other stakeholders. This challenge substantially increases with the remoteness of some mining areas. The management itself also requires such infrastructure. This is commonly provided in control centers. Data and information channels are bundled and allow for strategic meetings and coordinated decision-making.

Transferring such disaster management facts combined with the case study results led to the definition of Mine Rescue Management. The prior conclusions have been summed up to three central lemmas representing the long-lasting scenario of miners trapped underground, the need for evidence-based management and the tri-partite system approach including planning, response and learning. MRM has then been defined as “an evidence-based approach to prepare for, respond to, and learn from a long-lasting rescue of miners trapped underground.” (see p. 120)

The third lemma also gave the trichotomy for the formulation of MRM with its three key functions: Preventive planning takes place before the incident. During the incident, certain response principles are necessary to meet unplanned and individual challenges reactively. After the incident, an evaluative learning guarantees continuous improvement of both plans and response.

The planning section of MRM provided a structural framework by means of an organigram. The roles of the different, flexible modules are given. Afterwards, a staffing matrix provided suggestions regarding the internal or external assignment of the specified roles. That also included deputies and replacement schedules. Furthermore, MRM planning implies stakeholder lists as well as instructions for technical planning and control center set-ups.

Response within MRM relies on certain principles and basic strategies which allow for a flexible development of tactics during the individual incident. Parallelization and redundancy have already been given as examples of key strategies with respect to technological applications. Generic time series further led to defined MRM operations including search, support, rescue, and ground control. The identified best practices have been implemented and
arranged accordingly. Furthermore, leadership and logistics principles bring together learnings out of the fields of disaster management mentioned before.

Finally, **learning** enables and closes a cyclic approach for MRM. Systematic lessons learned out of the response itself can be implemented in the revising planning procedure. Besides continuous improvement within MRM, lessons must also be shared internationally and between agencies. Furthermore, it has been stressed that the MRM concept helps organizations to create new external experts for future missions.

The conclusion of this thesis provided both **discussion** and perspectives of the work done. The database showing many long-lasting entrapments in the 21st century so far and also the look into current trends and changes in national mine rescue organizations have proven the relevance of the conducted research. Furthermore, the discussion pointed out the possible application of re-designed rescue chambers to be considered as a preventive measure to the scenario of miners trapped underground.

Limitations of this thesis such as the exclusion of unsuccessful rescue missions provided the foundation for an approved **perspective**. The final MRM concept outlined the potential of international cooperation and shared standards. With respect to the European mining community, a European Mine Rescue Platform could help to realize the synergetic effects which have been identified in the heterogeneous national capacities as well as in the coordinated MRM approach. Finally, the chance of transferring valuable know-how of mine rescue back to the general field of disaster management has been named as a follow-up activity.
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## Appendix

### Appendix 1: Level 2 Code Distribution and Level 3 Coding

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Appendix 3: Structure of the Incident Command System

After Auf der Heide (1989)

Similarities to the CIMS (see Appendix 4) are shown in yellow.
Appendix 4: Structure of the Coordinated Incident Management System

Proposed structure for major incidents after Ministry of Civil Defence and Emergency Management (2005)

Differences to the ICS (see Appendix 3) are colored in yellow.
Appendix 5: Proposed Form of a Press Release

After Schön et al. s.a.:

**Explosion / Inundation / Accident at XY Mine**

(location), date – On the site of the XY Mine belonging to the ABC company at (location),
today (day/time of day), (date) around (time) it came to (incident).

In the mine there was an explosion / it came to an accident. At this point of time, it is not
clear if persons were affected.

The mine rescue teams were notified and are already deployed since (time). The responsible
authorities are informed.

Further details are not known to this point of time. We are going to inform the public when
more details are known. Current information about this incident can be found in the Internet
under (web address).

**Contact**

[...]

**Short profile of the company**

[...]
Appendix 6: Change-Over of Shifts


The numbers on the time-line at the bottom represent the time of the day on a 24-hour scale. M is a central meeting prior the four change-over steps A, B, C and D.

- **A**
  - Outgoing Incident Commander has attended operations briefing. Outgoing Incident Commander briefs incoming assisted by Planning Section.
  - Incident Controllers changeover.

- **B**
  - Outgoing operations and logistics management. Teams brief incoming teams. Operations and logistics management sections changeover.

- **C**
  - Operational section changeover as close as practical to the incident after being briefed.

- **D**
  - Planning/Intelligence changeover after assisting Incident Commander or operations sections changeover and briefing incoming planning personnel and review of Incident Action Plan.
### Appendix 7: Mine Rescue Management Positions

This table shows parallels and differences between the MRM and the CIMS concept. The MRM abbreviations are given in alphabetical order.

<table>
<thead>
<tr>
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<th><strong>CIMS Equivalent</strong></th>
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<tr>
<td>EO</td>
<td>Evaluation Officer</td>
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<tr>
<td>FUL</td>
<td>Finance Unit Leader</td>
<td>applies</td>
</tr>
<tr>
<td>GCUL</td>
<td>Ground Control Unit Leader</td>
<td>none</td>
</tr>
<tr>
<td>GSUL</td>
<td>Ground Support Unit Leader</td>
<td>applies</td>
</tr>
<tr>
<td>IO</td>
<td>Inter-Agency Officer</td>
<td>Liaison Officer</td>
</tr>
<tr>
<td>IUL</td>
<td>Information Unit Leader</td>
<td>Information Intelligence Unit Leader</td>
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<td>Logistics Manager</td>
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<td>Incident Controller</td>
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<tr>
<td>MUL</td>
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<td>applies</td>
</tr>
<tr>
<td>OM</td>
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<tr>
<td>PM</td>
<td>Planning Manager</td>
<td>Planning Intelligence Manager</td>
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