A Data-driven Framework to Reduce Diesel Spillages in Underground Mines

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Abstract: Several methodologies have been developed to manage diesel in open-cast mining due to its high demand and increasing diesel prices. Although the use of diesel-powered equipment in underground mines has increased over the years, effective management thereof has not received the same attention. With the advent of Industry 4.0, data can be utilised more effectively by modern businesses to identify and solve problems in a structured manner. In this study, an underground mine was used as a case study to determine whether a Data, Information, Knowledge, Wisdom (DIKW) method for diesel management could be coupled with the Six Sigma Define, Measure, Analyse, Improve, Control (DMAIC) tool to make more informed decisions and gain new insights to help reduce diesel wastage underground. The new integrated methodology identified diesel spillages and highlighted the biggest contributors to these underground spillages. The Six Sigma DMAIC domain utilised root cause analysis to determine the reason for recent systems failures, followed by the identification of practical solutions to eliminate up to 200 ML (megalitres) of diesel spillage. With this information, the case study mine stands to save over USD 175,000 per annum.

Keywords: DIKW; underground mine; diesel spillages; diesel management; root cause analysis

1. Introduction and Literature

Many countries rely on the excavation and export of mineral resources for the growth of their economy. One such country, South Africa (SA), is rich in mineral deposits, such as platinum and gold. Obtaining these deposits entails either open-cast or underground mining methods, depending on the mining depth [1].

Both mining methods are highly dependent on diesel usage to load and transport material. Recently, the mechanization of underground mines has been trending because of increasing global demands for mineral resources [1]. Typical underground diesel-powered equipment includes drill rigs, loaders, and dump trucks. Despite the more efficient operations of mechanised mining [2], operating costs are high because of operator, maintenance, repair, and diesel costs [3]. Consequently, the cost-effective management of diesel is becoming a priority for industries that utilise large volumes of diesel, such as underground mining [4].

Diesel prices in SA, specifically, have increased tremendously over the years and are expected to continue to rise. According to the South African Petroleum Industry Association (SAPIA), fuel prices increased by approximately 65% from January 2020 to December 2022. Additionally, haulage routes in underground mines are becoming far more extensive as mining operations delve deeper, increasing the cost of haulage operations even further [3]. Mining supervisors are therefore seeking more effective ways to operate mines, which includes diesel usage management.

A literature review was conducted to identify studies focusing on the underground mining environment, with the aim of reducing diesel usage and wastage to ultimately reduce operational costs. The studies were evaluated based on the following research criteria:

1. Was diesel management considered in the underground mining environment?
2. Was energy management, including diesel/fuel management, considered in the underground mining environment?
3. Did the study focus on the management/reduction of diesel particulate matter (DPM)?
4. Did the study focus on reducing diesel usage in equipment?

Extensive research has been conducted on the underground mining environment; however, the studies have not primarily focused on diesel usage and storage. The literature indicates that most studies focus on the management and reduction of DPM, as it poses a risk to human health [5]. Motlogelwa and Minnitt [6] focused on diesel management, but not on underground mining. Studies [7–11] focused on improving underground air quality conditions by monitoring DPM and the technologies that are used to manage it.

Studies [12–14] focused on optimising energy usage in underground mines; however, none of these studies considered the management of diesel fuel as an energy resource. Lastly, studies [1,3] focused on the use of diesel equipment in underground mines. By considering equipment life, equipment replacement, optimal working sequence, and travel-time predictions, mining personnel can repair and maintain diesel-powered equipment in underground mines more effectively.

Based on the findings from the literature review, a lack of research specifically focusing on diesel usage management in underground mines was identified. No methodologies have been proposed for the management and reduction of diesel usage in underground mines. Previous work [15] implemented the Data, Information, Knowledge, Wisdom (DIKW) hierarchy to assist with meaningful decision-making to manage diesel in open-cast mining.

The objectives of this paper were as follows:

1. Develop a method that identifies underground diesel wastage;
2. Integrate DIKW with DMAIC to identify root causes;
3. Improve the management and control of diesel.

2. Method

Several methodologies have been developed to manage diesel in open-cast mines due to their high diesel demand and increasing diesel prices. Previously [15], it was shown that the DIKW hierarchy can be applied to identify diesel wastage and theft in an open-cast mining environment. The work established DIKW as an effective diagnostic solution to assist mining companies with decision-making.

The study, however, did not determine the causes of failure or inefficiencies that result in diesel wastage. Similar to the DIKW hierarchy, DMAIC is a data-driven approach within Six Sigma that focuses on process improvement and problem solving [16]. Six Sigma's DMAIC is a tool that is used to find and eliminate wastage [17,18] and promote continuous improvement. This tool, however, is challenging to implement and is predominantly used by certified Six Sigma professionals [19].

With the DIKW hierarchy being easier to implement, the integration of these two approaches could result in a powerful tool that identifies, reduces, and controls diesel wastage. Figure 1 shows how this approach can be implemented.
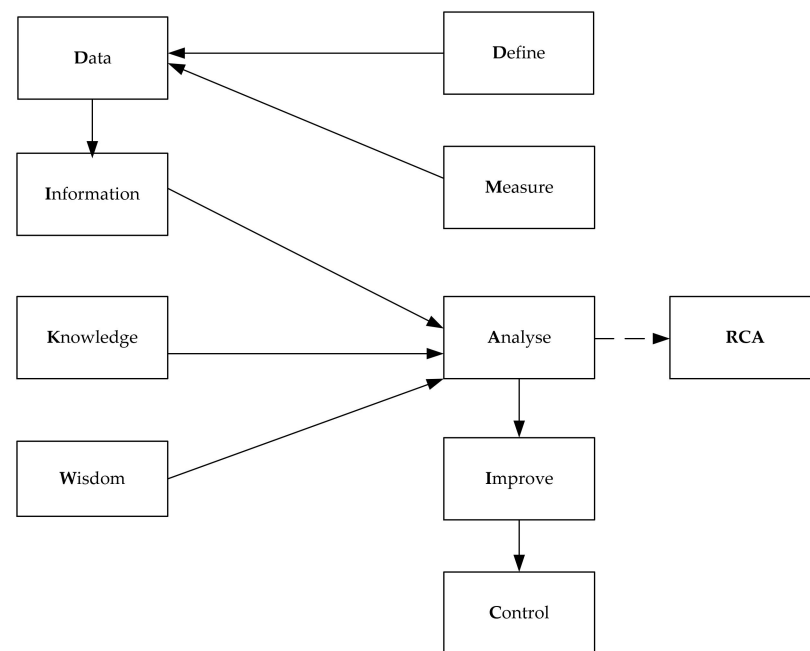
Figure 1. DIKW–DMAIC integrated approach for underground diesel management.

From the approach presented in Figure 1, the following process descriptions were formulated:

1. The Define and Measure components of DMAIC are aggregated into the data domain of the DIKW hierarchy, as follows:

    (a) **Define**—assesses the diesel distribution layout underground and the data availability.
    (b) **Measure**—identifies the available measurements taken by the operation.

2. The primary Analysis technique of DMAIC is conducting a root cause analysis (RCA) using a fishbone diagram, which entails brainstorming with an experienced team. It is difficult to identify root causes without fully understanding the problem. In this study, the analysis domain groups the last three pillars of the DIKW hierarchy together, namely Information, Knowledge, and Wisdom, and uses them as a foundation for RCA, as follows:

    (a) **Information**—organising, structuring, and condensing the collected data [15].
    (b) **Knowledge**—selection of key performance indicators for the specified system.
    (c) **Wisdom**—development of reports for stakeholders to review.

3. The **Improve** component entails generating possible mitigation strategies to solve the identified issues and causes, i.e., utilising the wisdom obtained to tailor the solution.

4. The **Control** phase entails prioritising and setting up control mechanisms to ensure that the implemented improvements are sustained.

Root cause analysis (RCA) is the process of determining the root causes of problems to identify appropriate solutions [20]. The benefit of Six Sigma is that the RCA is already embedded in the process.

3. Results and Findings

An underground mine was used as a case study to test the approach shown in Figure 1. This section addresses its application, explaining the procedures and how it was used in practice. The case study mine is situated in the Free State province of South Africa. The underground mine is a trackless mine, implying that large volumes of diesel are needed to carry out operational activities, such as exploration, loading, and the transportation of ore material.

In a previous work [15], the application of DIKW was divided into two domains: the data domain and the analysis domain. This study follows the same principle but integrates Six Sigma's DMAIC tool, adding components that do not form part of DIKW, namely RCA, improvement, and control.

3.1. Data Domain (Define and Measure)

The data domain is elaborated by the Define and Measure phases of Six Sigma. The domain is summarised in two sections, namely assessing existing data collection methods, followed by assessing available measurements.

3.1.1. Define: Construct a Diesel Distribution Layout and Assess Available Measurements

Understanding the basic diesel distribution layout was the first step to evaluating the various data points available in the network. Figure 2 indicates the flow of diesel from purchase (receipt) to use (disposal). Three devices were used to capture data per shift, as well as sensors that ran for 24 h per day:

- Device 1—measured diesel delivered on the surface and the level of diesel in the tank;
- Device 2—measured diesel issued from an underground tank at level 263 to underground vehicles;
- Device 3—measured diesel issued from an underground tank at level 282 to underground vehicles;
- Sensor 1—measured diesel outflow from the surface tank to an underground tank at level 263;
- Sensor 2—measured the level of diesel in underground tank 1 (263 X/cut 8);
- Sensor 3—measured diesel outflow from tank 1 to tank 2 (L282 X/cut 19);
- Sensor 4—measured the level of diesel in tank 2.
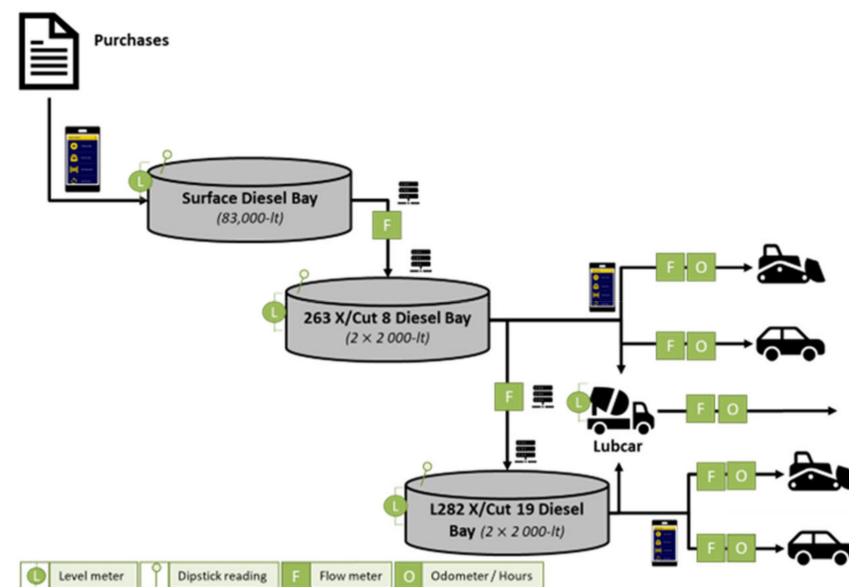
Figure 2. Diesel distribution layout and management at the case study mine (from [21]).

3.1.2. Assess Data Collection Methods

Due to the nature of underground mining operations and limited accessibility, data was collected using different methods. Communication between the surface and underground was made possible through remote communication technologies [22]. This system architecture involves inner control loops managed by a network of local programmable logic controllers (PLCs) and an outer control loop managed by a central supervisory, control, and data acquisition (SCADA) system. This ensures complete control and monitoring of the entire PLC network, making it a popular technology for data acquisition in underground

mines [23,24]. Figure 3 illustrates the data flow process from SCADA sensors to the SCADA database.
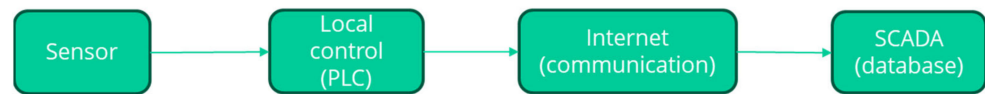
Figure 3. Typical SCADA architecture.

In the current case study, sensors were installed to measure tank storage levels. These data were accessible through tags. The tag data were linked to the control room, where automatic control was implemented. The tank levels triggered the relevant pump, thereby transferring diesel from the surface tank to underground.

In parts of the case study mine where SCADA was not available, data were captured on a mobile application via a diesel bay attendant and then synchronised with a centralised online database. To ensure the completeness and accuracy of the data, diesel attendants were also required to manually capture the data on diesel control sheets that were hand-written (also useful for backups). Figure 4 illustrates the manual data collection procedure. Here, a mobile application was used for capturing data and a manual sheet was used in parallel to avoid data loss. The two systems were compared to verify the dataset.
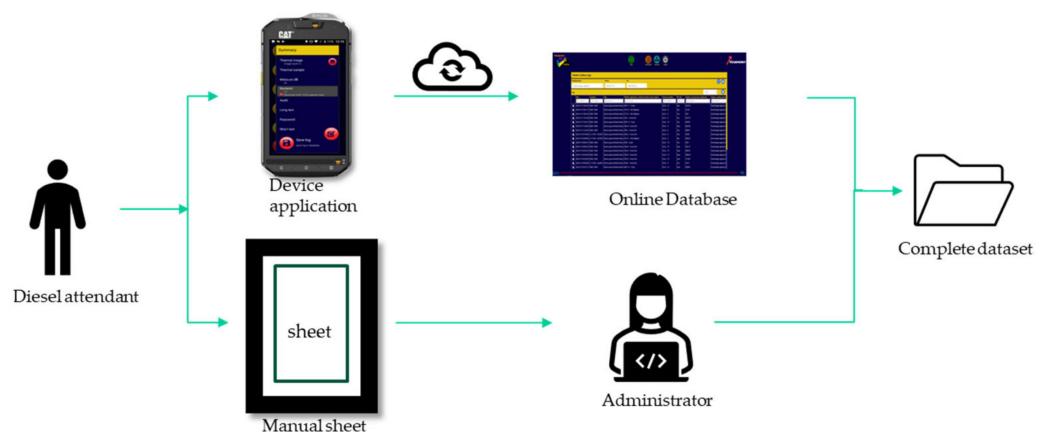
**Figure 4.** Manual data collection method used at the case study mine.

3.2. Analysis Domain

3.2.1. Integrate Information, Knowledge, and Wisdom

In Figure 1, the Analysis phase of Six Sigma integrates Information, Knowledge, and Wisdom from the DIKW hierarchy. This step transformed the data obtained from the underground operation into useful information. This was achieved by contextualising the data to understand what each data point represented. The next step, converting the information into knowledge, was performed by first selecting key performance indicators (KPIs). For this study, a full audit trail of diesel, from purchase to use, was important. The KPIs that needed to be evaluated were therefore as follows:

- Total diesel purchased/received;
- Total diesel within the tanks;
- Total diesel disposed per vehicle;
- The type of vehicle.

From the KPIs, data profiles were constructed on Microsoft Power BI (Figure 5). Note that other data management platforms can be used for the same end result.
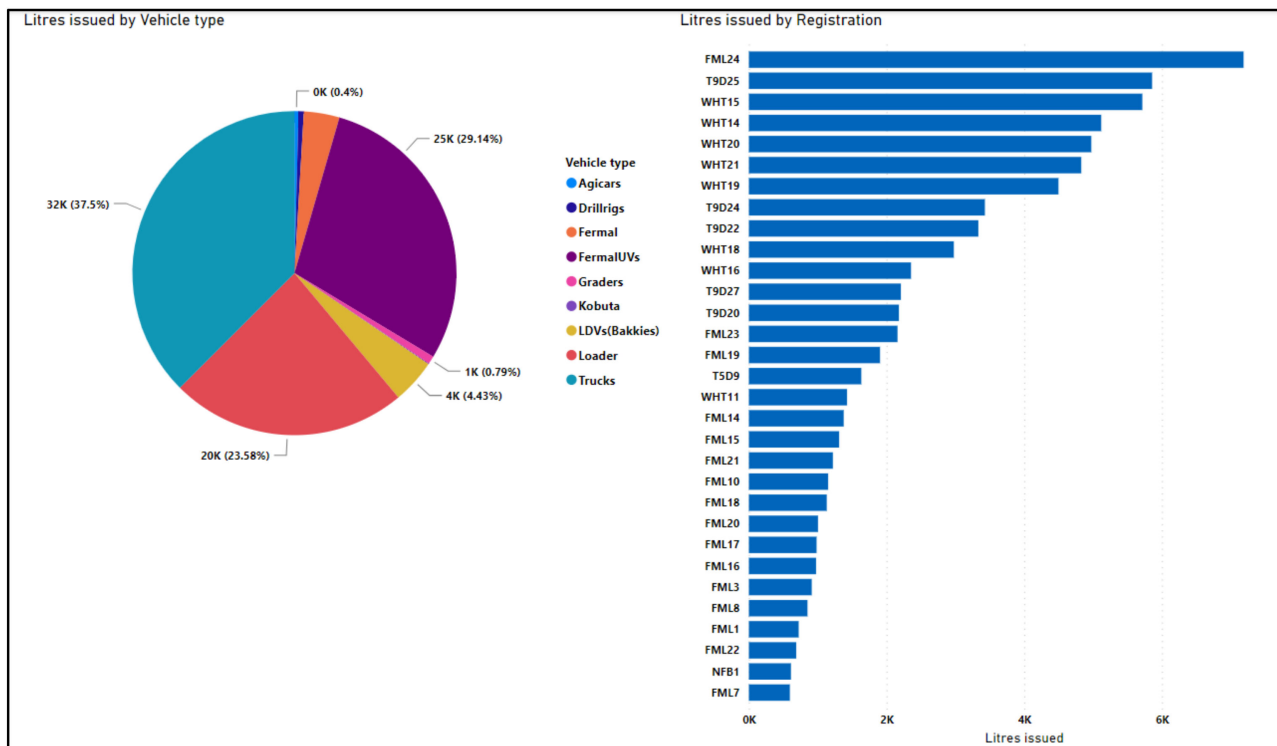
Figure 5. Case study mine's underground diesel distribution by vehicle (**left**) and by registration (**right**) using Power BI.

Figure 5 depicts the case study mine's underground distribution of diesel volumes. The dashboard allowed managers and different stakeholders to understand and visualise their diesel consumption. The pie chart (Figure 5, left) indicates the types of vehicles utilised underground as well as their consumption for the period of one month. From the chart (Figure 5), the highest-consuming vehicles could be identified, firstly, as trucks, followed by fermel UVs and, thirdly, loaders. This was expected, as these vehicles are used for primary activities in underground mines.

Figure 5 also shows a clustered bar chart (Figure 5, right) which indicates the diesel issued per vehicle registration. This representation enabled managers and stakeholders to visualise a specific vehicle's consumption, with the top vehicle being the highest consumer and the last being the lowest consumer.

Diesel was received and stored in the surface diesel tank then transferred to level 263 (2121 m below the surface) through a pipeline and into another storage tank. From here, the diesel was transferred to a lower level, level 282 (2274 m below surface), where it was stored until used at the diesel bays.

By visualising the periodic diesel balances, a more comprehensible indication of amounts of diesel supplied, stored, and used was able to be conveyed to stakeholders.

Table 1 was constructed on Power BI and indicates monthly balances of diesel usage underground from the point of receipt to the point of use. From January 2022 until March 2023, there were diesel losses during each month, except for two months (May 2022 and August 2022). Two equations were used to quantify the losses:

$$C_{dip} = O_{dip} + Q_p - Q_i \tag{1}$$

In Equation (1), C_{dip} equals the calculated closing dip of the tank in litres, O_{dip} equals the opening dip reading at the beginning of the month, Q_p equals quantity of litres purchased/delivered, and Q_i equals total issues (in litres) disposed during the month.

$$E_{Loss} = C_{dip} - C_{dip,m} \tag{2}$$

In Equation (2), E_{Loss} is the estimated losses, and $C_{dip,m}$ is the actual measured dip meter reading using the dip stick probe.

Table 1. Case study mine's monthly diesel balances.

Month (Year)	Opening (L)	Purchases (L)	Disposals (L)	Closing Calc (L)	Closing (L) Actual	Losses (L)
January 2022	d	135,495	101,013	88,961	67,232	21,729
February 2022	67,232	75,978	85,938	57,272	27,752	29,520
March 2022	27,752	110,037	103,870	33,919	29,688	4231
April 2022	29,688	113,882	102,102	41,468	33,494	7974
May 2022	33,494	75,908	96,827	12,575	12,575	0
June 2022	12,575	147,586	95,319	64,842	47,212	17,630
July 2022	47,212	110,126	93,196	64,142	51,528	12,614
August 2022	51,528	77,488	102,295	26,721	26,721	0
September 2022	26,721	114,750	99,064	42,407	22,192	20,215
October 2022	22,192	148,270	109,284	61,178	43,092	18,086
November 2022	43,092	106,086	97,314	51,864	18,977	32,887
December 2022	18,977	92,739	64,274	47,442	44,506	2936
January 2023	44,506	75,902	73,612	46,796	28,531	18,265
February 2023	28,531	69,428	73,849	24,110	18,188	5922
March 2023	18,188	140,766	86,144	72,810	67,935	4875
Total Losses (L)						196,884

Using Equations (1) and (2), the overall diesel losses were able to be quantified. The values highlighted in red in Table 1 provide the decision makers with knowledge of the problem and the wisdom to start with the investigation. Application of the DIKW hierarchy method confirmed that frequent diesel spillages occurred during transferral from the surface to the underground tank. Inefficiencies in underground diesel usage were therefore successfully identified using the Analysis domain.

Integrating the Information, Knowledge, and Wisdom pillars of the DIKW hierarchy provided a solid basis from which to conduct a root cause analysis (RCA) of the spills. RCA is an important part of Six Sigma and is a key component of the Analysis phase of DMAIC. If Six Sigma had not been integrated with DIKW, the losses from spillages would not have been evident. Next, an RCA was conducted to identify the root causes of diesel spillages underground. RCA not only identifies a root cause to the problem but can resolve immediate and obvious symptoms of the problem [25]. The next section shows the application of Six Sigma's RCA to the case study mine.

3.2.2. Finding Root Causes

The purpose of RCA is to diagnose a problem, determine the root cause, and arrive at a solution. When the root causes of a problem are known, corrective action can be taken to ensure that the problem does not reoccur [25]. There are various methods for evaluating the root cause of a problem, for example 'cause-and-effect analysis', 'six sigma', 'fishbone diagrams', 'the 5 Whys method', and 'fault tree analysis' (FTA), to name a few [25,26]. Although most studies that utilise Six Sigma use fishbone diagrams to determine root causes, any RCA technique may be utilised. FTA is predominantly used in situations that involve failures and accidents [27].

3.2.3. RCA Application in Case Study

After a site inspection at the case study mine, it was confirmed that the losses were a result of diesel spillages. However, there was no clear understanding of the causes of the spillages. Consequently, an FTA was applied to arrive at the key root causes of diesel spillages underground.

FTA is considered one of the simplest and most effective methods of improving system reliability [27]. By applying this method, an organisation can determine a logical relationship between the failure that has occurred and the causes that resulted in the failure.

FTA is a top-down, step-by-step approach used to determine the root cause of a problem. The starting point of the fault tree is the undesired event, also known as the top event. This event is followed by logically determining the immediate contributory fault conditions that resulted in the top (undesired) event using OR and AND gates [27,28]. The contributory causes/faults are listed until primary causes are obtained. There are three main events on an FTA analysis, namely the top event, the basic event, and the undeveloped event (an event that is not broken down further) [29].

3.2.4. RCA Results

After conferring with management at the case study mine, a qualitative FTA was created, as presented in Figure 6. The figure indicates the top event, diesel spillages, which was informed by integrating Information, Knowledge, and Wisdom into Six Sigma's Analysis phase, followed by possible causes and their possible causes until arriving at the root cause(s).
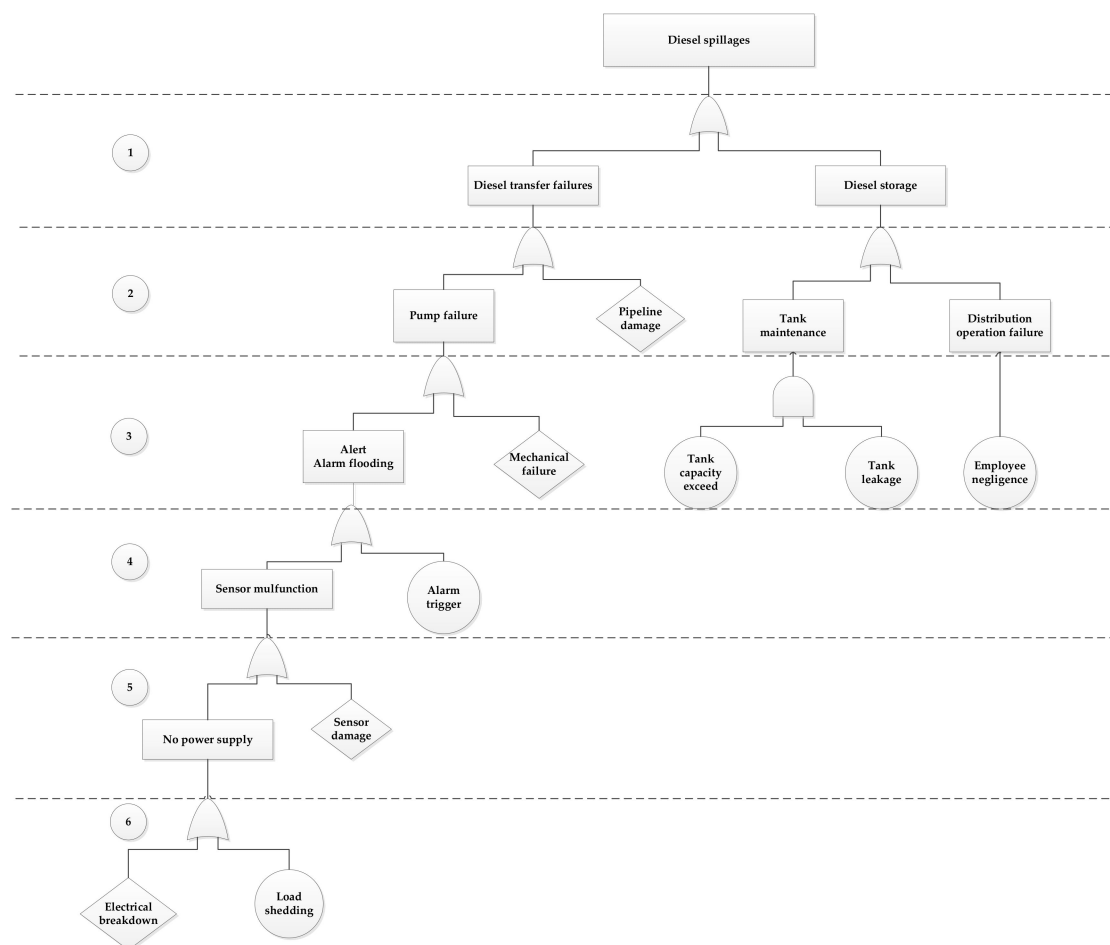
Figure 6. Fault tree analysis graph for underground diesel spillages at case study mine.

The development of an FTA is an iterative process since causes can change over time. It is important to ensure that the identified causes are the result of an exhaustive and unbiased process, which is achieved through constant communication between all stakeholders. In the current case study, the relevant stakeholders were the maintenance team, the store coordinators responsible for receiving diesel, instrumentation technicians, diesel bay attendants, engineers, and managers. The FTA was categorised into different consultation and auditing levels to ensure that all possible causes were considered.

Level 1: This level was based on process knowledge and observation. Spillages can occur during diesel transfer and at the point of storage. Consulted stakeholders included the store coordinators and engineers who approved the observation.

Level 2: Here, events identified in Level 1 were deemed the 'effects', and their causes were subsequently evaluated. Audits were undertaken on the transfer pipelines with the support of the maintenance team and technicians. Two additional causes were identified: *pump failure* and *pipeline damage*. No damage was identified during the audit, however, classifying *pipeline damage* as an undeveloped event. *Pump failure* was explored further.

Diesel bay attendants are responsible for maintaining diesel storage. Investigations into causes of failures within the diesel storage facilities were undertaken. Two intermediate events were identified: *tank maintenance* and *distribution failure*. These two events were explored further in Level 3 of the FTA.

Level 3: The maintenance teams and technicians indicated that *pump failure* may occur due to either *alert-alarm flooding* (where the pump is not stopped when needed) or the *mechanical failure* of the pump. The latter was considered an undeveloped event because, during the investigation, the maintenance team evaluated the mechanics of the pump and found that the pump was functioning as it should. Also, a weekly pump evaluation schedule at the specific case study mine ensured that the pumps were always mechanically functional.

Three basic events were identified through the diesel bay inspection, as they played an integral part in spillage. The storage tank had not undergone maintenance in several years, as management was never informed about the required maintenance.

Levels 4 to 6: In these levels, *alert-alarm flooding* was further explored. This involved engagements with instrumentation technicians, control room operators, and mine engineers, who confirmed the *alarm trigger* to be the basic event. When the control room experienced multiple alarms, some alarm triggers were ignored by the operators based on the alarm event's consequences. *Sensor malfunction* was identified as another cause but, due to the frequency of sensor inspections in the case study mine, it was considered an undeveloped event.

Sensors require an electrical power source to operate. The time of spillages had a common pattern; it was noted that they mostly occurred during *load shedding* or load curtailment. Power from offices was curtailed during night shifts, and the diesel distribution system sourced electrical energy from the same grid. During these times, the power supplied to the diesel network would fail.

Further investigations were conducted, and it was found that the sensor read zero during power outages, which triggered the pump to start running and transfer diesel underground. The pump would continue pumping diesel until control room operators manually stopped its operation.

All causes were agreed on by all consulted stakeholders at the case study mine, resulting in the fault tree analysis graph shown in Figure 6.

The basic events (root causes) were found to be *loadshedding*, *alarm triggers*, *exceeded tank capacity*, *tank leakages*, and *employee negligence,* as indicated by Figure 6.

The mine management was made aware of the root causes using Figure 6 and was able to find direct solutions and make effective decisions. The next section describes the identified improvement measures to be implemented.

3.3. Improve

Managers and other stakeholders were now aware of the causes of diesel spillages at the case study mine. The next task was to ensure that the system's performance improved (i.e., reduce spillages), as guided by DMAIC. Table 2 summarises their observations and possible mitigation plans.

Table 2. Root cause observation—possible mitigation plan to prevent diesel spillage.

Root Cause	Observation and Possible Mitigation Plan
Load shedding	Observation: Load shedding resulting in no power supply is the main cause of sensor malfunction. During loadshedding events, underground tank level sensors read zero, thus triggering the surface tank pump to start pumping diesel. If this is undetected due to alarm flooding, the pump will continue running, resulting in higher volumes of diesel being wasted. Mitigation: Load shedding is a new normal in SA and is predicted to continue. The best way to avoid power failures in sensors is to purchase and install uninterrupted power supply (UPS) systems. These units are designed to supply electric power to devices during power outages, thus ensuring that sensors do not malfunction.
Alarm trigger	Observation: An alarm is an audible or visible means of indicating process deviation or abnormal conditions to the control room operator [30]. At the case study mine, the average amount of alarms received per day is around 2000. Underground mines comprise intricate systems with many alarms, resulting in numerous alarms being triggered (alarm flooding). This can ultimately overwhelm operators, which leads to many of these alarms being disregarded [30]. Diesel spillage alarms are often ignored in the case study mine, as they are considered a lower priority compared to other alarms. Mitigation: An alarm management procedure using Engineering Equipment and Materials Users Association (EEMUA) guidelines should be developed [30,31]. In this guideline, it is stated that all alarms are useful and should never be ignored. Management should ensure that no alarm is without a response and that there is a monitoring system in place.
Tank capacity exceeded and tank leakage	Observation: These two basic events are linked; lack of maintenance and regular inspection results in diesel spillages. The case study mine was commissioned in 2002 and has been operational for over 20 years to date. The demand for diesel in this mine has increased over the years. However, the diesel storage capacity has been kept the same. Mitigation: Regular maintenance checks will enable managers to react quickly to diesel leakages, resulting in minimised spillages. Increased diesel tank capacities will also prolong the starting time of diesel spillages, giving control operators more time to react to the triggered alarm.
Employee negligence	Observation: Diesel bay attendants should ensure safe and efficient distribution and diesel storage management. Attendants tend to focus only on issuing diesel to different vehicles and do not assess the condition of the diesel bay. Mitigation: A procedure should be put in place to encourage diesel bay attendants to be more alert. Diesel bay attendants should not wait for control room operators to detect the alarm. Phones are made available underground and should be utilised to communicate failures with the control room.

3.4. Control

In the previous section, root causes of diesel spillages in an underground mine were determined. These causes were identified in order to expand the DIKW hierarchy and enable effective management of underground diesel wastage. Upon identification of the root causes, the study developed a priority matrix to prioritise solutions with the highest impact on the diesel-loss problem experienced in underground mines. In Figure 7, the second quadrant indicates the solutions that are high impact and easier to implement. These solutions can be implemented within a short timeframe. The fourth quadrant indicate solutions with a low impact and high difficulty to implement.

Increasing tank capacity has a minimal impact and is difficult to implement because it necessitates the mine having a budget for these tanks as well as going through multiple approvals before execution. The operation would have to shut down for this to be implemented. Although the solution is not impossible to implement, it requires effort.
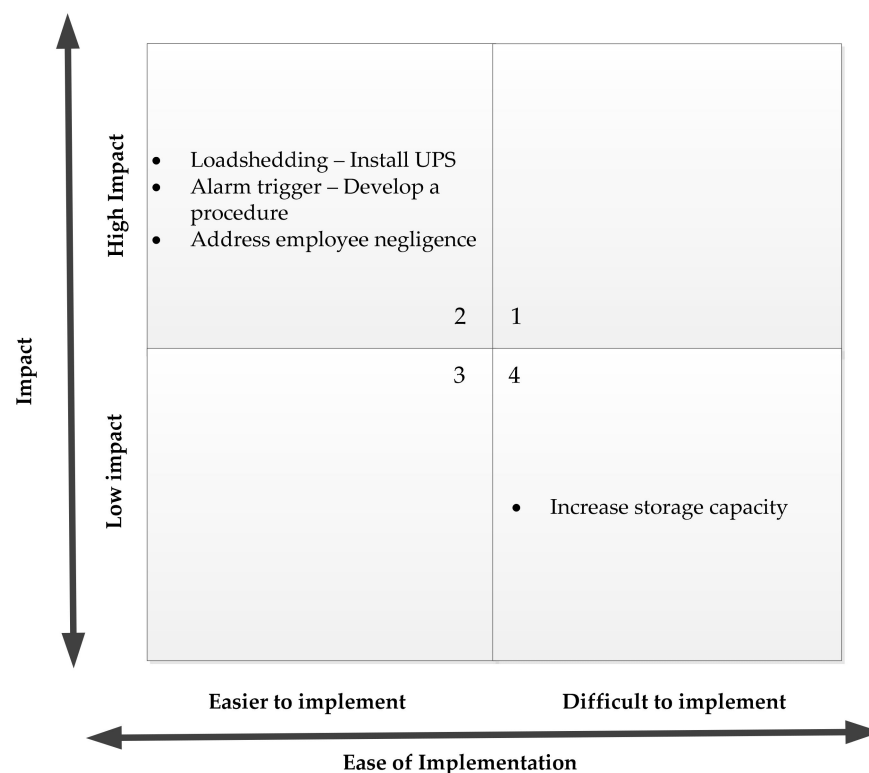
Figure 7. Priority matrix for solution implementation at case study mine.

With this approach, a total loss of 196,884 L (Table 1) could have been avoided (13,126 L per month over 15 months). Mitigating these causes would result in average diesel cost savings of USD 15,000 (ZAR 269,079) per month and an estimated USD 175,000 (ZAR 3.2 million) per annum for the case study mine (at a diesel cost of USD 1.11 (ZAR 20.50) per litre).

South Africa has over 150 surface mines and over 50 underground trackless mines. With extrapolation, the method presented in this paper can potentially save the mining industry in South Africa over USD 35 million per year.

4. Conclusions

Diesel usage in underground mines has increased over the years; however, the management thereof has not kept pace. Storing diesel fuel underground is not so difficult in principle, with ample literature available on the underground mining environment; however, no studies have focused primarily on diesel usage and wastage management. The DIKW hierarchy method was integrated with the DMAIC tool for use in this study to identify diesel wastages at a case study mine and assist management with more effective decision-making. The study resulted in a powerful data-driven framework termed 'DIKW-DMAIC'.

The method was applied to a case study mining operation to identify causes of spillages underground. The method allowed managers to not only diagnose the problems but also identify the root causes. The study also provided decision makers with mitigation strategies and subjected them to a priority matrix to expedite the implementation process. With this methodology, diesel losses of up to 200 ML could have been avoided, resulting in savings of approximately USD 175,000 (ZAR 3.2 million) per annum.

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