3D PRINTING SPARE PARTS ON DEMAND

Project Documentation

Team 16 of INF3011F 2023

Content

Business Case & Project Outcomes

Background

The Council for Scientific and Industrial Research (CSIR) is a leading scientific and technology research organisation that focuses on researching, developing, localising and diffusing technologies to accelerate socioeconomic prosperity in South Africa. The CSIR is the oldest research organisation in Africa, and it is an entity of the Department of Science and Innovation of South Africa. It was established through an Act of Parliament in 1945 and the organisation's executive authority is the Minister of Higher Education, Science, and Innovation.

The CSIR undertakes many projects that aim to find innovative solutions to the problems faced by technical and scientific industries in South Africa. One such problem is 3D printing mining spare parts on demand, for which the CSIR has enlisted UCT's INF3011F Team 16 to be their project team to ideate solutions to the problem that will be explored further below.

To best meet their needs, it is vital to understand what CSIR, as an organisation, aims to achieve. The business objectives must be continually kept mind when moving forward and ideating any solutions.

Business Objectives

The CSIR focuses exclusively on finding solutions to problems involving science and technology and does research in those fields. Here is a more comprehensive summary of what the CSIR aims to achieve as an organisation:

- To conduct research, development and innovation of transformative technologies and accelerate their diffusion.
- To accelerate socio-economic prosperity in South Africa through leading innovation.
- To provide industry-relevant solutions (using emerging technologies) to support different industries in South Africa.
- To build and transform human capital and infrastructure.
- To diversify income and maintain financial sustainability and good governance.
- To achieve all its objectives in a sustainable manner.

With the overall goals of CSIR in mind, the project team could then focus in on what the current situation of concern of the project at hand was.

Current Situation of Concern

The problem that the CSIR aims to solve by undertaking this project is that of providing spare parts to asset-heavy organisations, most especially mines, since it has been found that these organisations in high-value industries face challenges when it comes to having timely access to spare parts when undertaking their daily activities/operations.

To understand the situation of concern underlying this project, the project team decided to employ Design Thinking principles by producing an Empathy Map to gain insight into the needs of the user. The Empathy Map can be found under Appendix A.

From the Empathy Map, the team gathered that the main factor that contributes to the problem is the fact that many mines are in remote areas and as a result, struggle to obtain spare parts within reasonable time periods, negatively impacting mining business operations. The issue of remoteness means that mines also struggle with obtaining specialised or rarely used parts from local suppliers. Furthermore, the equipment is often outdated and, as per Hartmut Brodner – the Business Development Manager for the Mining Cluster Council for Scientific and Industrial Research (CSIR), "Inventory degrades in the yards over the years" meaning keeping warehouses stacked with spare parts presents more issues.

Through conducting further meetings with the project sponsors and discussing the different depths of the problem, the project team discovered more critical information.

To mitigate the issues presented by the remoteness of mines, some suppliers have begun to consider additive manufacturing i.e., 3D printing solutions to address these problems. The benefit of 3D printing mining spare parts on demand is that it allows for a shorter design-to-product time. It also means that parts that are more complex in design and structure can be easily printed via just-in-time and on-demand production. However, there are challenges that arise from this solution and this project will be focused on addressing the following issues:

- The Intellectual Property (IP), especially that of the original equipment manufacturer (OEM), needs to be managed securely to ensure only authorised access to OEM CAD/CAM schematics and thus prevent unauthorised printing of spare parts as well as to ensure that designs are not tampered with.
- The Design Engineering procedures that need to be followed to print these spare parts with the optimal strength and functionality.
- The quality of these 3D printed spare parts needs to be assessed to guarantee safety-critical, quality assured, certified parts.
- Decisions are yet to be made about where these parts will be printed and whether there will be a need for transportation.

Given the information above, it was concluded that the CSIR needed the project team to develop a solution that would:

- ensure the authorised sharing of CAD schematics.
- ensure that the 3D printed parts are quality assured.
- involve a safe and reliable method of transporting the printed goods between the printing facilities and the mines.
- Offer a realistic printing premises.

By providing a solution that caters to all the above-mentioned issues, access to 3D printed spare parts could then be facilitated to mines.

Before ideating solutions to these problems, the project team needed to consider any assumptions and constraints surrounding the situation of concern to get an even more complete picture of the situation. The critical assumptions and constraints are explored below.

Critical Assumptions and Constraints

After extracting the relevant information from the project sponsors and then employing Design Thinking principles to delve deeper into the factors surrounding the problem by asking “why”, the project team developed a fuller idea of the scope of the problem. However, to lay out the field of the project, the project team had to make certain assumptions and, to make sure that the solutions that were to be ideated later were feasible and viable, the project team had to identify any constraints that the project would have. These assumptions and constraints are detailed below.

Assumptions

- The project team assumed that the solution that would need to be provided would be applicable specifically to the mining industry.
- The project team assumed that qualified professionals would handle the more complicated parts of the solutions that would be ideated later. For example, quality assurance would be done by people who are trained to do so.
- Since 3D printing can be quite costly, it was assumed that the most cost-effective strategies would have to be suggested.
- It was assumed that the ideated solutions would have to be environmentally sustainable to be in line with the values of the CSIR.
- The project team assumed that since the CSIR was interested in innovation in the field of science and technology, the CSIR would then be open to unconventional but feasible solutions.

Constraints

- Time:
  - The project was administered over the course of three months and due to its large scope, this amount of time was limiting as there were various aspects of the project to be explored leaving minimal time for necessary activities such as testing.
- Resources:
  - Due to the lack of resources that were specific to the project (i.e., metal 3D printers), the project solutions were mainly be based on research as there was no chance to physically print or implement the solutions.
- Lack of expert knowledge:
  - The team did not have any prior industry (additive manufacturing, mining, blockchain) knowledge.

After the assumptions and constraints were identified by the project team, it was then time to identify which parties would be impacted by the implementation of the final solution so that these external stakeholders could be kept in mind when ideating the solutions. This information is depicted using a stakeholder context diagram below.

External Stakeholder Analysis

As can be seen from the context diagram below, the external stakeholders that were identified were the transport companies that would transport the 3D printed spare parts, the 3D printing professionals, the miners, the mines, the quality assurers, the OEMs (Original Equipment Manufacturer), the CSIR as well as government officials. The role that each external holder would play is depicted on the context diagram below.

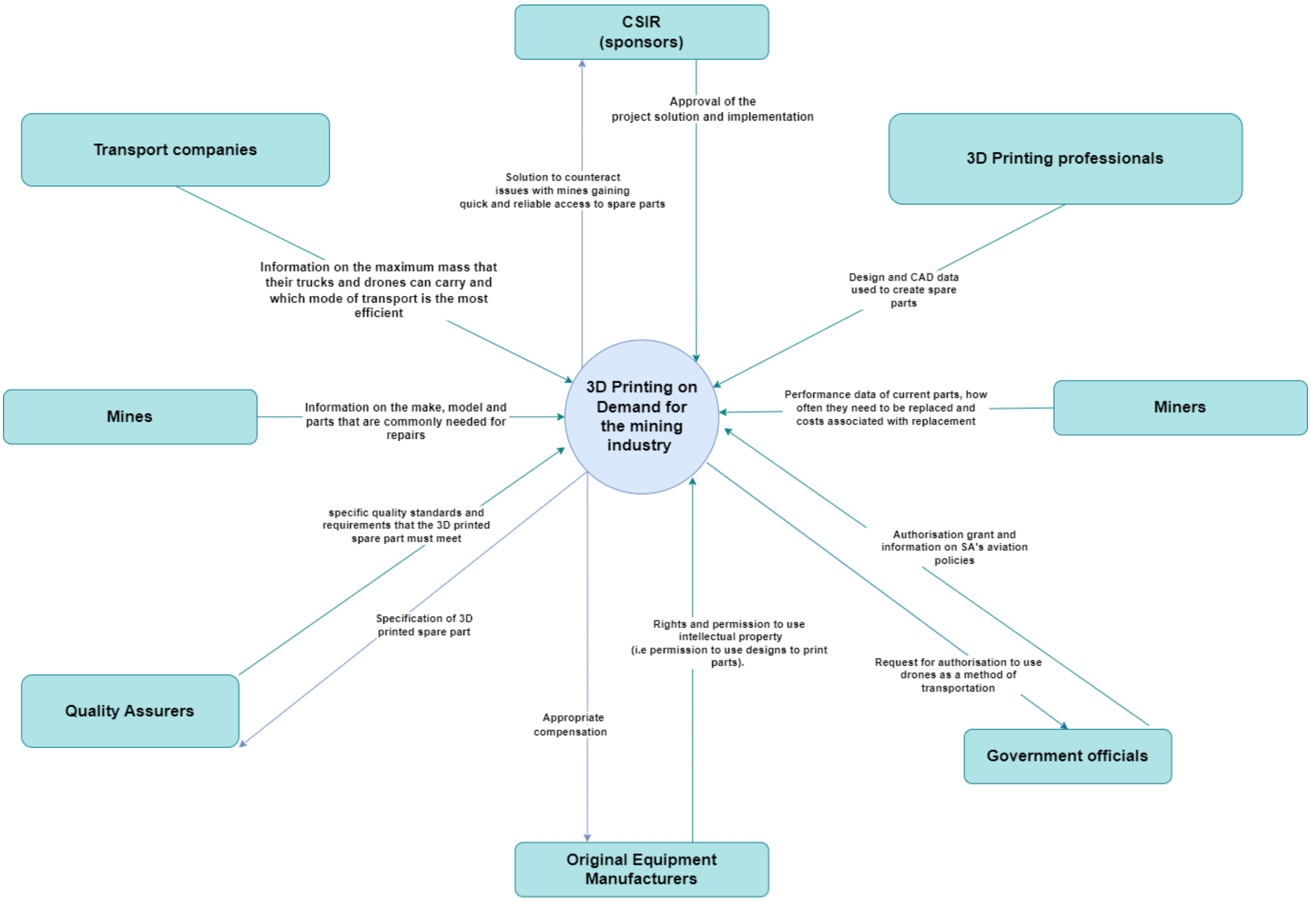

Figure 1 - Internal Stakeholder Diagram

Once the external stakeholders were identified, solutions to the problem were then ideated. Keeping these key players in mind, the solutions are detailed in the section that follows.

Proposed Solutions/Ideas

The process of providing the service – 3D printing spare parts on demand – is a complex one. There are many variables involved and many stages within this process. Let us first explore the high-level process, and then investigate the different tasks within this process.

Figure 2- process of the 3D printing on demand service

Explanation of process

The process begins when a part first breaks on-site at a mine. The mine owners/workers then need to notify us of what part has broken and needs replacing. We will print, fine-tune (detailed explanation later), and then quality assure the part. Once we assure that the part is safe to be used, we need to deliver it to the mine site.

From this process, we identified 5 critical/focus areas. These focus areas are tasks within the process that each need a solution. These 5 critical tasks are:

- Printing premises
- Intellectual property (IP)
- Fine-tuning
- Quality assurance
- Delivery/Form of transportation

Rather than providing rigid solutions to the entire process, the project team proposed multiple solutions for each of these 5 tasks/focus areas. This means that the sponsor could have, for example, chosen solution 1 for IP, solution 3 for fine-tuning, solution 2 for quality assurance, and solution 2 for delivery. The project team would then investigate and research these chosen solutions further as the final solution. This approach granted the sponsor much greater solution variety, control, and freedom to choose the solutions that best met their required criteria.

The explanation and proposed solutions for each of the 5 critical tasks follow.

Printing premises

Printing premises pertains to *where* the printing of spare parts would take place. The choice of premises would impact the implementation cost and would affect the way in which other solutions would be implemented. Feasibility and viability of the entire solution rested partly on this aspect. There were two options with regards to printing premises – on-site and off-site. The explanation, and viability and feasibility of the two options are explored below:

On-site printing: (Solution 1)

The printing of spare parts on the mining premises. This would require that printers be transported, kept, and managed at the mines.

- Advantages
    - The challenge of transporting printed spare parts to remote areas would be avoided.
    - There would be a decreased negative impact by vehicle emissions on the environment as there would be less transportation involved.
    - Transportation costs would be decreased significantly, if not completely removed.

- Disadvantages
    - The transportation of many printers and an array of varied materials to the site would be costly and risky.
    - The storage of many printers and an array of varied materials on the site would be costly and risky.
    - The delicate printing machinery would be imperilled under the harsh conditions of mines.
    - Other tasks involved, for example, quality assurance, would need to be carried out on-site.
    - Powering the 3D printers in remote areas could be challenging.

Off-site printing: (Solution 2)

The printing of spare parts at a separate location from the mining premises. The parts will be printed at pre-existing 3D printing factories.

- Advantages
    - Printing and other tasks involved in the process (e.g., quality assurance) would be done on the premises of the company that specialises in the task. The company could therefore make full use of all its resources – ensuring maximum quality and efficiency.
    - A greater range of products could be printed as there would be access to more printers and materials.
    - There would be no need for expertise/workers to be sent to work on the mines.

- Disadvantages
    - The remoteness of the mining site would become a significant challenge.
    - The frequent transportation of spare parts to the mining site would become costly.
    - The frequent transportation of spare parts would likely become harmful to the environment overtime.

Hybrid: (Solution 3)

After considering on-site and off-site printing, the project team ideated further and considered an option that would allow them to leverage the advantages of both, whilst minimizing their disadvantages. This became the hybrid solution.

Building on this solution, the question became: How much of the 3D printing would be done on-site and how much would be done off-site? Using historical data and information of the mining company and project, we can estimate the parts that will need replacing.

It may be estimated, for example, that 90% of the parts that would need replacing were steel objects with a maximum height and width of a meter. It would then be the case that only steel (the raw material) and the printers that can print steel objects of size one by one meters would need to be on-site. The advantages and disadvantages of the hybrid solution are explored below:

- Advantages
    - Parts that break often (e.g., steel parts) could be printed on-site and there would be no transportation delays as no formal delivery would need to happen.
    - Only the essential printing materials and equipment would be kept on-site so less storage would be needed compared to the on-site solution.

- Disadvantages
    - The hypothesis that “90% of parts that break are steel parts” may be an unreasonable and unreachable target.
    - Some on-site storage is still needed for the on-site printing part of the solution.

To conclude, three solutions were proposed to the project sponsors to address the challenge of where parts would be printed. They were on-site, off-site, and a hybrid printing solution from the solutions.

Fine Tuning

Once products have been printed, they need to go through a process of fine tuning and post processing to ensure that they are ready to be quality assured and deployed.

Fine tuning refers to the process of adjusting or changes to something to ensure the desired maximum performance or appearance. In the context of 3D printing, a large aspect of fine tuning is *support removal*. This is explained and discussed further below.

Supports are added structures that offer support to printed objects and need to be removed after the printing process. In the context of metal 3D printing, supports are especially vital for holding down printed objects and preventing distortion because of stress from the high processing temperatures. They act as anchors that prevent the object from destroying itself. Supports are ideal in ensuring that an object is printed well, however, there are some notable downsides to the use of supports during the 3D printing process:

- Support structures are made with the same material as the printed object meaning that there is a waste of resources as the material cannot be re-used for printing of other objects
- There exists no single use support removal tool (especially in the case of metal printing) so supports would take time to remove as they would need to be removed individually and manually
- There exists the possibility of damage to printed objects due to dents from support removal

With these downsides in mind, we proposed no-support printing solutions:

VELO3D (Solution 1):

The VELO3D is a printer that provides support free technology. It provides many positives, such as mitigating some of the issues highlighted above. But it also comes with its disadvantages

Advantages	Disadvantages
The technology offers design freedom as clients do not have to optimise their designs to fit requirements of supports	The technology is expensive and offers cost constraints
Support Free technology is maximised for 3D printed objects dedicated to the transfer of heat and flow of fluids	Limited types of products can be printed with this technology
Eliminates the time and chance of damage to original printed objects factor	

Table 1 - advantages and disadvantages of the VELO3D printer

Re-orienting/re-design object in the printing chamber (Solution 2):

With the assistance of individuals with some knowledge on Design concepts for Additive Manufacturing, printed parts can be redesigned or re-oriented in the print chambers in a manner that allows for printing of easily removable supports.

Specialised Team of professionals to remove parts (Solution 3):

It is difficult and sometimes impossible to completely do away with supports in 3D printing. And so, we proposed a solution that deals with supports in printing.

Using a specialised team of trained professionals, support removal for printed parts can be an organised process in the production of the parts. These individuals will be trained on the efficient techniques and the optimal use of the necessary tools to remove parts. This will lead to reduced cases of dented and damaged parts, especially in the case of 3D Metal Printing.

In the case of Polymer 3D Printing, (as there exists some equipment within the mining industry made of different polymers), easy and efficient removal of supports can be guaranteed by:

- Reducing support material density during the printing process
- Providing enough clearance between supports and models
- Making use of supports that are soluble

Once a printed product has undergone thorough fine tuning and all supports have been clearly removed, it is now deployed to the quality assurance phase where it will be tested against industry standards

Quality Assurance

Furthermore, another aspect of the problem that the project team considered was the quality assurance. The project team realized that there needed to be measures in place to ensure that the 3D printed spare parts met the requirements of the OEMs and could perform up to the same standards that traditionally manufactured parts do.

This meant that the 3D printed parts would need to be strong and able to withstand the high temperatures and harsh chemicals/substances that are encountered underground and at mining operations. It was also concluded that the quality assurance goes together with OEM's trust of their CAD schematics with the company i.e., the OEMs would only trust the mines with their CAD schematics because they know that the printed spare parts are well quality assured.

Given the importance of quality assurance, it was concluded that there would only be a single, yet very rigorous solution that incorporated various means of ensuring that the parts that would be printed were going to be strong and to ensure that they would be tested well enough for OEMs to be confident in their quality. To implement this, the project team came up with a four-step approach to the solution:

Step 1: There would first need to be an agreement between the mines and the OEMs about the strategies that would be used when 3D printing the parts as well as which types of tests would need to take place to quality assure the equipment (these are specified below). Furthermore, agreements on which trained personnel would come to quality assure the parts would need to be detailed within that agreement.

Step 2: This step would focus on making 3D printed parts stronger. The project team found out, by doing further research, that 3D printed products are notorious for not being as strong as their traditionally manufactured counterparts and that this would pose a big problem in situations such as these, whereby the parts would really need to be strong and durable because they were going to face harsh conditions and would have to bear great weights. It was concluded that having parts that are not strong enough would simply be a waste of money as these parts would break even sooner than traditional parts; it would also be a waste time and materials. So, the project team decided that a helpful approach to 3D printing these parts would be to try to get it as right as possible, as soon as possible to prevent a waste of resources. This would entail using 3D printing mechanisms and methods that would result in stronger parts being printed. Here was the list of methods:

- Increasing the Infill Density: Through further research, the project team found that the structural integrity of 3D printed parts really mattered as one would not want the parts to collapse while being used. A way to ensure structural integrity would then be to increase the infill density. This would entail making the interior part of the 3D printed part denser. The interior density of a 3D printed part ranges from 0% to 100%, where zero would mean totally hollow and 100% would mean completely solid. For mining purposes, the printing workers would need to get the parts to as close to 70% interior density (this was because an infill density of up to 70% has shown to produce stronger parts and there are diminishing returns from having an infill density that is greater than 70%)

- Increasing the wall thickness: Another measure that was identified that could possibly aid in making 3D printed parts stronger was to increase wall thickness. Wall thickness is simply how thick the interior wall of the 3D printed part is. Increasing the wall thickness was identified to be very important in making 3D printed stronger as printed parts experience more strain on the outside than they do on the inside. Furthermore, increasing wall thickness would improve the quality of parts that are in shapes that are difficult to print (called overhangs).

- Using thinner layers: printing the parts using thinner layers rather than thicker ones would mean that there would be more adhesion and density between the layers that follow each other. A downside of this was that printing would then take longer (however, it would still be a shorter process compared to having purchase new parts and deliver them all the way from the OEMs).

- Using strong infill pattern: The project team identified that using the "right" infill pattern would go a long way in strengthening 3D printed parts. The infill pattern would go hand in hand with the infill density and acts as an internal support structure for 3D printed parts. A recommended way to make 3D parts stronger was to use a dense infill pattern ranging from 30% to 50% since the type of infill pattern would directly influence how strong the parts would be. Below is a visualisation of the many different types of infill patterns for reference:

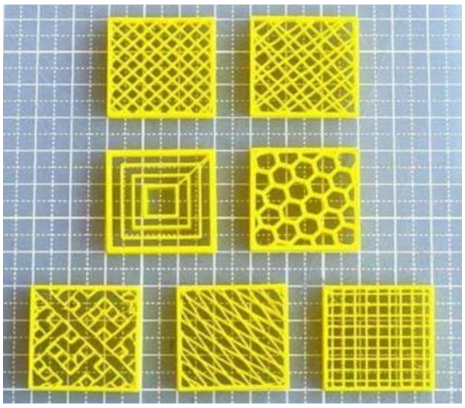

Figure 3 - assorted infill patterns

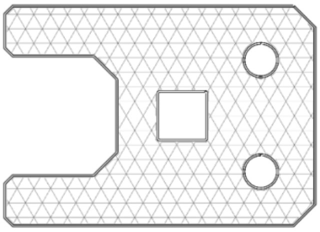

Figure 4 - triangular infill pattern

A triangular infill pattern: A triangular infill pattern was an example of an infill pattern that would allow for stronger 3D printed parts because using such a pattern would mean that parts would have a decreased chance of deforming. This infill pattern would also provide a good support structure. Printing speeds would be improved because of the straight-line movement of the printhead.

A rectangular infill pattern: With this sort of infill pattern, 100% infill density could be achieved because of its grid of parallel and perpendicular extrusions. This infill pattern would also have a higher printing speed because of the straight-line movement of the printhead.

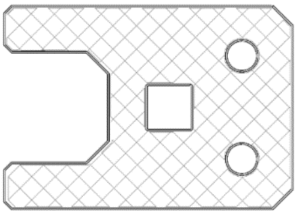

Figure 5 - rectangular infill pattern

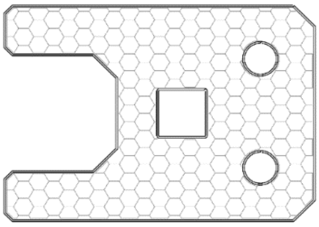

Figure 6 - hexagonal infill pattern

A hexagonal infill pattern: This infill pattern was an option as it would have tessellated hexagons as well as the highest strength to weight ratio. However, it would take longer to print because hexagons are not as straightforward as triangles or rectangles.

- Reduce Cooling: Upon further research, it was found cooling affects the adhesion of layers after setting and that cooling the parts too soon after printing them could reduce the adhesion (this would result from layers that are next to each other not being able to bond with one another). However, how cooling would occur would depend on the type of material that is used to 3D print the part. The cooling rate would need to be reduced in relation to the material that is being used.

Step 3: This step would involve performing quality control tests on the parts. The testing of parts was identified to be a significant feature of the quality assurance process as it would ensure that the parts comply with the standards stipulated by the OEMs. It would also enforce trust between the printing parties and the OEMs as the OEMs would have trusted them with their CAD schematics. The following were the different types of equipment testing that would need to take place, as identified by the project team with the help of a UCT final year civil engineering student:

- Strength testing: Strength testing would be a type of testing that assesses the strength or durability of a material.
- Materials testing: Materials testing would be focused on looking at how different materials react to different pressures and weights.
- Thermal testing: Thermal testing would measure how a material would respond to changes in temperature.

The types of tests listed above were not exhaustive. There were various types of testing that could be done. The project team only touched on the most popular types of testing and made the assumptions that the appropriate personnel would be hired or deployed to conduct and oversee the testing and that if further tests would need to be performed, that would take place.

Step 4: This step of the solution entailed going through steps 2 and 3 iteratively until it was found that the 3D printed parts indeed met the standards stipulated by the OEMs. Only once the 3D parts only failed within a reasonable confidence interval would they be rolled out to the mines. This part of (almost) perfecting the 3D printed parts would not take long as roll-out of the parts would be only done once it was determined that the parts were indeed ready.

The advantages and disadvantages of this solution are listed below:

- Advantages
    - A more rigorous way of quality assuring the 3D printed spare parts would mean that all the parties involved know that the parts are indeed quality assured.
    - Having a signed agreement between the printing parties and the OEMs would ensure that both parties act accordingly.

- Disadvantages
    - Because the solution was so rigorous, it would take up a lot of resources such as time, money, equipment, and personnel.

    - Because of the variety of parts, how much it would cost to quality assure different parts would vary.

NB: It is important to note that there could be no assessment of advantages and disadvantages of the quality control testing as it was a standard procedure that needed to be performed on mining equipment.

Furthermore, the project team moved on to ideate solutions regarding protecting the intellectual property (CAD schematics) of the OEMs. This was further elaborated on in the section that follows.

Transportation

Transportation was another aspect of the larger problem that the project team needed to address. This pertains to the different modes of transportation that could be used to deliver 3D printed spare parts to mines. There were many different modes of transportation that the team brainstormed, and we settled on trucks and drones. The solutions are further elaborated on below.

Trucks: (Solution 1)

Over the years, trucks have been used as the traditional transportation method. It is an efficient way to ensure that necessary components and equipment are transported reliably to be made readily available for mining operations.

After doing some research, the project team found that there are companies who specifically transport spare parts for mines in South Africa (e.g., Jacobs Transport, Robeck Logistics and Special Envoy etc). These companies could be used for local transport of spare parts, especially if the mine is considerably far from where the 3D printer is situated. Trucks can be used to transport larger parts, whereas smaller hatchbacks or motorcycles can be used to transport smaller spare parts. There are a few things to keep in mind when it comes to using trucks:

- It is important to plan the route carefully to ensure that trucks can safely navigate through the terrain and reach the mining site in a timely manner.
- There must exist some sort of quality assurance to ensure that the trucks have enough load capacity to transport the required spare parts.
- The spare parts must be stored properly to prevent damage during transit (this may involve securing the parts with padding or straps to prevent movement).
- Regular maintenance of the trucks is essential to minimise breakdowns and ensure that the spare parts arrive at the mining site on time.
- The communication channels between the truck drivers and the mining personnel must be kept open to coordinate the delivery of spare parts.

To assess the viability and feasibility of this solution, we explored the advantages and disadvantages of using these trucking companies.

- Advantages
    - Trucks can transport large capacities and quantities of spare parts efficiently, especially over long distances

    - There are already companies within South Africa that have been around for decades and provide specific transport methods for mines (trucks included)
    - The fact that these companies have been around for so long, it increases reliability and provides some assurance that the company will be able to transport spare parts safely, without damaging them during transit
    - Trucks provide efficiency and enable spare parts to be transported in a short amount of time, resulting in less downtime when it comes to production levels within the mine.

- Disadvantages
    - The rising cost of petrol will be an issue, especially if the mine is far away from the off-site 3D printer.
    - There is a safety risk, especially if the truck needs to use the highway to transport the spare part, the likelihood of an accident taking place and causing damage to the spare part increases.
    - The use of trucks for transportation can contribute to carbon emissions resulting in air pollution.
    - Trucks cost a lot to be maintained and must be serviced regularly to ensure that damages and breakdowns do not occur

Drones:

Transporting spare parts using drones is a new and innovative concept that offers several benefits. Drones work by using a combination of sensors, GPS, remote control, and on-board systems to fly and navigate through the air. Even though drones have not been used to transport spare parts for mines before, there has been an extensive amount of research to use drones as a mode of transportation within a South African context. Like trucks, there are a few things to consider when using drones as a mode of transportation:

- It is important to understand the capabilities of the drone before it is used for transportation of spare parts. The drone should be able to carry the weight of the spare part and travel the distance required to reach the mining site.
- The route should be planned carefully to avoid potential hazards, such as high winds, low visibility or interference from other drones or aircraft.
- The spare parts should be protected from damage during the flight by using secure packaging methods.
- There are many rules and regulations to adhere to when it comes to owning and using a drone in South Africa
- It is essential to have communication between the mining site personnel and the drone operator, to ensure that the spare parts are delivered to the correct location and received by the appropriate personnel.
- It is important to have safety measures in place to ensure that error handling takes place if something goes wrong. These methods include backup power systems and emergency shutdown procedures.

To assess the viability and feasibility of this solution, we explored the advantages and disadvantages of using these trucking companies.

- Advantages
    - Drone transportation is very efficient and provides a quick method of transporting spare parts.
    - It does not use any fuel and limits the air pollution produced by traditional transportation methods.
    - Transporting spare parts by drone can help reduce the risks associated with traditional transportation methods, such as accidents and injuries to drivers and passengers.
    - Drones can reach remote locations that may be difficult or impossible to access by traditional transportation methods. This can be particularly useful for mining operations in remote areas

- Disadvantages
    - Drones are only able to transport spare parts that have a certain mass.
    - Drones are limited to the length of the distances it can travel within a single trip before it needs to be charged again.
    - Drones can be affected by adverse weather conditions, such as high winds or heavy rain, which can restrict their ability to fly. This can result in delays or cancellations of transport services, which can have serious consequences for mining operations.
    - Drones can be vulnerable to interception or hacking, which can compromise the confidentiality and security of the spare parts being transported.

Hybrid (Solution 2):

There can be a hybrid implementation whereby trucks are used to transport larger parts between the 3D printer and the mine and drones can be used to transport smaller parts.

The project team realised, during their research, that the preferred solution would depend on a variety of factors. These factors include the distance between the 3D printers and the mine, the weight and size of the spare part, the availability of transport infrastructure and the cost of transportation.

Intellectual Property:

Simply put, one cannot reprint an existing part and resell it as one's own. This leads into one of the main issues that surrounds the printing of 3D parts – intellectual property and data rights management mechanisms for protecting unauthorised access and downloads of OEM CAD/CAM schematics.

Some possible solutions to ensure that digital rights/IP of CAM/CAD schematics are protected are listed below are various mechanisms that work to ensure the protection of digital rights.

1. Watermarking the digital files: by embedding a unique code or symbol that can identify the source of the content.
2. Encrypting the files by converting the CAM/CAD schematics into a code that can only be accessed by a decryption key. Ensures that only authorised individuals can view or print the schematics.
3. Access control: restricting access to the cam/cad schematics to only authorised devices or individuals through password or user authentication
4. Digital signatures: To authenticate the origin as well as integrity of CAM/CAD schematics and ensure that they have not been tampered with.
5. Digital rights management technology: to protect digital content from being copied or distributed without permission.

Use *Fortinet (*which is an integrated, multi-layered solution to safeguard organisations) uses next generation firewalls. Has identity and access management as well as network access control.

A combination of these strategies could be implemented to achieve the best possible outcome in the protection.

Strengths and weaknesses:

Each of the methods followed in protecting intellectual property have their strengths and weaknesses. For example, while digital signatures may be easy to add, to establish ownership of content, they can just as easily be ignored or removed. The same is true for watermarks which are a visible instrument used to combat unauthorized usage, they can also dampen the user's experience with the product. Digital rights management technology proves to be expensive and vulnerable to hacking although it has wide use in protecting unauthorised access to CAD schematics. Encryption is also a method known for providing strong protection, but it can also limit content usage. Considering the strengths and weaknesses of each method will ultimately play a huge role in establishing which method is best to use.

Implementation Of Methods:

Step 1: Coming to an agreement: OEMs and mines to share the CAD/CAM schematics. This will require some legality to ensure that OEMs receive remuneration for their designs, and they aren't ripped off by 3D printing companies.

Step 2: Finding a way to ensure that these transactions: exchange of digital files of designs happens in a secure manner and protected. Two solutions to this secure transaction of CAD schematics are proposed:

Blockchain (Solution 1):

This is the most efficient manner to conduct these transactions and have some sort of ledger stored to keep track. Microsoft Azure has a blockchain service that can be accessed as a service.

Digital Warehousing (Solution 2):

Another viable solution includes using a digital right management technology such as Seal Path software to send the files and complete transactions.

- Access control by a software platform such as Tresorit may also be a good method to share these digital files.
- The printed materials will be subject to quality assurance checks down the line as per the legal agreement.

Final Solution

After presenting the solutions to the project sponsors, the project sponsors selected the solutions that they preferred. With the sponsor's chosen solutions, the project team could then go ahead investigating and researching further into each aspect to produce the final solution. From the feedback provided by the project sponsors, a deeper understanding of the project requirements was gained. It was found that, before being able to provide the service of 3D printing spare parts on demand (shown in Figure 2), an entirely separate process will need to first occur. This process will enable us to provide the service of 3D printing and start the other process in Figure 2. To distinguish between these two processes, they will be referred to as Phase 1 and 2. Phase 1, the *pre-process*, is explored below.

Phase One

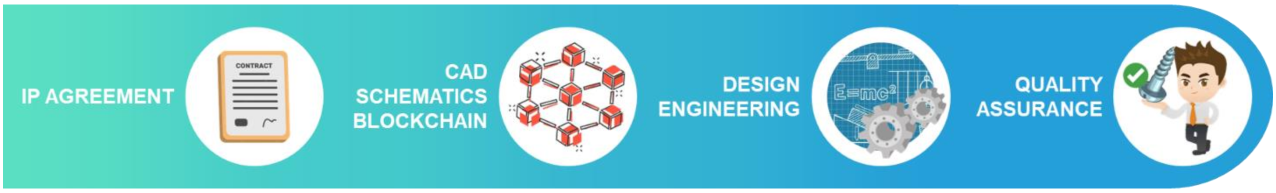

Figure 7 - pre-process to be undertaken before the main service can be provided.

Explanation of process

To begin this process, an agreement will need to be made with the OEMs to provide access to their intellectual property - their CAD schematics - in return for remuneration of some sort. Once an agreement is reached, the OEMs will send us their CAD schematics. This is where blockchain plays a vital role in the safe and secure transfer of these schematics. With the schematics of the traditionally designed parts in hand, the parts then need to be designed and refined specifically for 3D printing. This is known as design engineering. Finally, these designs will be tested, and the parts quality assured to ensure they are safe to use on-site.

The explanation, research and proposed solutions for each of the 4 areas in this process follows.

Intellectual Property Agreement

This is the initial step needed for the protection of Intellectual Property of the OEMs and to ensure that the 3D printing personnel receive the required resources (CAD files) via the signing of an agreement. The following is a prototype of the agreement that outlines the terms and conditions of the exchange of designs between the two entities.

(See appendix B agreement)

CAD Schematics – Blockchain

With the agreement established, it is then key to ensure that the digital files are efficiently and securely transferred from the Original Equipment Manufacturers to CSIR for additive manufacturing. Formidable intellectual property protection and astute digital rights management are imperative for these digital files. These digital files are referred to as Computer aided design drawings/ CAD schematics. They are software generated digital drawings that use symbols to represent the various components of a system and connections between them. CAD schematics can later be developed and fine-tuned for 3D printing. These schematics will provide the rules and instructions to the 3D printer for how to print a specific object.

For IP protection and digital rights management, the sponsor chose blockchain as their preferred solution. “Blockchain is an advanced database mechanism that allows information to be shared in a transparent manner within a secure network”.

Blockchain is an innovative technology, and using blockchain smart contracts[1] would ensure that all the requirements that are needed for such a sensitive transfer of information are met. These include the confidentiality and integrity of the files, as well as the availability of information regarding those who accessed the files. The CAD files will only be seen by the intended authorized individuals.

We have identified that using a decentralized system with the Ethereum[2] blockchain, Smart Contract and Interplanetary File System (IPFS) is the best implementation of the digital files transferring process as per Yasmeen Alsman and Amas Abu Taleb’s extensive research from Princess Sumaya University of Technology.

Proposed System Model for Blockchain Implementation

A web application will be built using React: it will serve for the interaction with the blockchain. This is the interface that CSIR and OEM members will use to send and receive the files to IPFS.

IPFS is a protocol and network that allows peer to peer file storage and sharing system. Each file is identified by a unique content hash rather than where it may be located. This is where the CAD files will be stored and may be retrieved later.

A connection from the website to the blockchain will need to be established using Node JS[3], Truffle development environment[4] to compile and deploy the smart contract: it will enforce the terms of a contract which are simply the conditions of the signed legal agreement that has already been reached.

Ganache application[5] will be used to test and deploy the smart contract written on a local Ethereum network, all made possible through Meta Maske[6] which will allow us to run Dapp[7] without a real Ethereum node.

User Journey of Proposed Solution

With the smart contract deployed: It will allow existing users to log onto the network or register with the system if they meet the requirements for engagement.

Senders (OEM) will be able to upload the files and receivers (CSIR/printing company) can download the files from the IPFS using an extremely secure encryption and decryption key method.

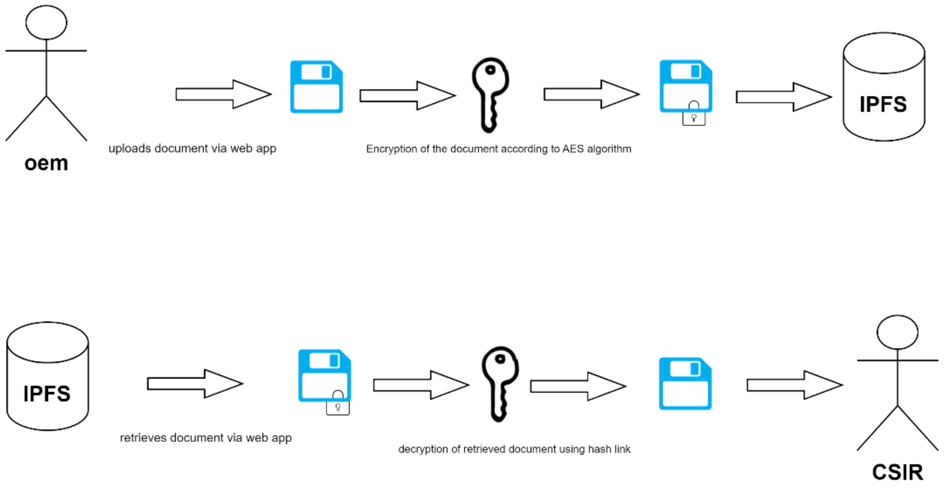

Figure 8 - Encryption and decryption protocol in the proposed system

High overview of the Proposed System Model:

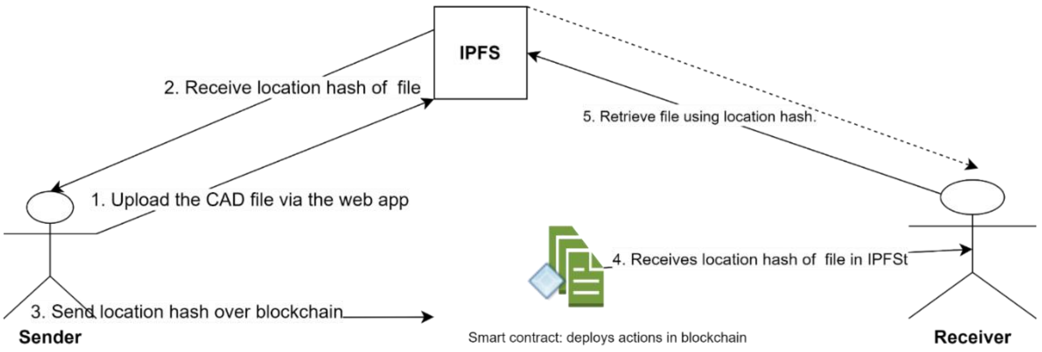

Figure 9 - Proposed system of blockchain implementation

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1. Smart Contract: "It is a set of rules and regulations encoded on a blockchain that automatically execute when predefined conditions are met. "
2. Ethereum: "A decentralized, open source blockchain platform that enables creation of decentralized applications and smart contracts. It has its own cryptocurrency that is used as a payment method on the network."
3. Node JS: "An open source, cross platform, JavaScript environment that executes JavaScript code outside of a web browser. It allows for building scalable, high-performance web applications and APIs."
4. Truffle development environment: "This is a development environment that enables the testing and debugging of smart contracts. "
5. Ganache application: "A personal blockchain for Ethereum development that allows testing and deployment of smart contracts on a local Ethereum network. "
6. Meta Maske: "A popular wallet and browser extension that allows users to interact with the Ethereum network and decentralized apps built on the Ethereum blockchain.
7. Dapp: "Any software application has been designed to run on a decentralized network based on blockchain technology."

Design Engineering

An important aspect of Additive Manufacturing is Design Engineering. This vital process can begin once the necessary CAD schematics and legal agreements have been signed and received. Simply put, design engineering is the redesigning of parts specifically for 3D printing. It involves the expertise of designing and deciding on the printing procedures to be followed to produce 3D printed products that are as high quality and up to the same standards as traditionally made parts. In the context of 3D printing on demand for mining industries, design engineering is especially important to ensure high quality, safe, and cost-effective parts. The ability of additive manufacturing to produce parts of equal strength but at lower costs is one of the greatest advantages AM offers. All the advantages can be leveraged if a thorough design engineering approach is followed.

To achieve this, a 3D Printing Design Engineering Manual (prototype) has been developed with the following objectives:

1. The manual directs the process to be followed when printing 3D parts (metal or non-mental) on-site or off-site
2. The manual highlights the procedure from receiving CAD files of a spare part to the printing of the actual part
3. The manual will ensure the printing of objects that align with the requirements of all mining parts

Structure of the Manual

The following is a breakdown of the different sections covered by the manual.

Section 1: Part Analysis

In the event of a broken part, operations will need some way of determining whether the broken part is suitable for 3D printing or not. Additive Printing proposes many advantages, however, there are some parts, with a primary focus in the mining industry, that are not 3D printable. Operation leaders will need a way to accurately identify these products. This section will ensure that:

1. Only parts viable for additive manufacturing are printed. This will prevent the changes of wasted resources (funds, time and skill) and deploying dysfunctional parts
2. Only objects of suitable material and size are printed (e.g., materials that burn instead of melting under high temperatures are not suitable for 3D printing)

Section 2: The Printing

The printing process contains the following steps, which will be outlined in the manual. These steps are applicable to both onsite and offsite printing facilities, unless otherwise stated.

1. Retrieval of CAD files from OEMs *(this step is conducted beforehand)*
2. Slicing processes

Slicing is a necessary step that translates CAD files into instructions that are perceptible by the 3D printer in the form of geometric code. This process is necessary to ensure that the printed objects are of great quality and make use of the best time and resources available. By optimising the different functionalities of slicing software, designers can ensure maximum printing.

Section 3: Post Processing

The post processing section will detail the activities (such as fine tuning and support removal) that need to occur after an object has been printed. These activities occur before the quality assurance and deployment of an object. They ensure that the accurate finishing touches have been completed.

The above-defined manual (prototype) can be found in Appendix B.

Once the design engineering principles have been followed thoroughly, printed parts are able to proceed to the quality assurance phase.

Following a thorough design engineering approach highlighted in the manual will help to best utilize the advantages that AM has to offer. When design engineering has been completed, the parts can be 3D printed, and the actual physical parts can then be quality assured.

Quality Assurance

Once the spare part has been printed (following the employment of the design engineering techniques mentioned above), quality assurance on this physical part will need to take place to ensure that the parts will perform up to the standards stipulated by the OEMs. This is detailed below.

After the first iteration of solutions, it was decided that the quality assurance of spare parts will solely focus on performing quality control tests. Below is a list of 3 tests that will be performed (Note that this does not prescribe what tests need to be done for every kind of part but simply explores the wide possibilities of quality control testing that could occur):

Strength testing

Strength testing is a type of testing that assesses the strength or durability of a material. To strength test a material, that material will be subject to mechanical or physical stresses, and this will help evaluate the extent to which it will be able to withstand or resist the forces that are applied to it. Strength testing will be particularly important as it will help prevent failures, accidents and other unfortunate events that can occur because of utilising weak or defective parts. There are different types of strength tests. One very important test is tensile testing which will measure the amount of force a material can withstand before it finally breaks. Another type will be compression testing which will look at the part's ability to resist being crushed or contorted under pressure. Stress testing is another type of strength testing that will assess the equipment's ability to withstand very heavy loads and forces.

Materials testing

There are many different types of materials testing. For example, hardness testing will be used to measure the resistance of materials to deformation and wear; this will be important when it comes to mining equipment that is used in abrasive and high-stress environments.

Thermal testing

Thermal testing is a process that measures how a material responds to changes in temperature. It will be used to understand the behaviour of materials at different temperatures to ensure that said materials will be safe, reliable and able perform up to standards. Seeing as mining conditions are particularly extreme, it will be important to perform tests that can ensure that the printed part will not get damaged while in use. This will involve subtests such as thermal conductivity testing which will look at the extent to which material can transfer heat through conduction. This will be very important as mining conditions are very harsh, and they experience extreme temperatures. Moreover, a 3D printed part that is a very good conductor of heat could injure a miner when the temperatures are particularly high. Furthermore, thermal expansion testing will look at how the part may expand or contract under varying temperatures and thermal shock testing will assess the ability of a spare part to withstand sudden changes in temperature. Thermal testing will be used to detect anomalies or defects in the mechanical components of mining equipment such as pumps and motors. To accomplish this, specialised equipment such as thermal chambers, thermocouples, or infrared cameras to monitor temperatures and collect data will need to be brought onto the printing site.

Bear in mind that the 3 types of tests listed above are not exhaustive. There are various types of testing that can be done such as flexural testing, shear testing and fatigue testing (these look at the material's ability to hold out against repeated stresses over time). This document only touches on the most popular types of testing and makes the assumptions that the appropriate personnel will be hired or deployed to conduct and oversee the testing and that if further tests need to be performed, that will take place.

Finally, once the 3D printed spare parts meet the OEM's requirements, the implementation of the project will then be able to move on to Phase 2 which focuses on providing access to 3D printed spare parts to mines. Phase 2 is expanded on below.

Phase Two

Figure 10 – new and refined process of the 3D printing on demand service

With the completion of Phase 1, we can now enter Phase 2 and begin to provide the service of 3D printing on demand to mines. This process was summarized in the first iteration by Figure 2. However, with the new inclusion of Phase 1 (which was not yet present in the first iteration), there are some differences to this process in the final solution.

Unlike Figure 2, the above figure no longer includes *quality assurance* as a part of this process. This is because quality assurance is now a part of the initial process – Phase 1. This is the same for intellectual property and fine-tuning. Both need to already have been addressed in Phase 1 (although fine-tuning is still displayed in the above figure, design engineering has already been performed to specify exactly how the fine-tuning process will occur).

From this process, we identified 3 critical/focus areas:

- Ordering of spare parts
- Printing premises
- Delivery/Form of transportation

Ordering Spare Parts

When a mining equipment part breaks or a certain spare part needs to be acquired, mining representatives (i.e., mine manager, worker, or individual in charge of acquiring spare parts) will make use of the CSIR application to place orders for desired parts. The app will offer the following functionalities:

- Creating a profile

This feature will allow mining representatives to create profiles for their respective mines on the system. Through this profile, orders and spare parts can be placed, orders can be tracked and information on the printability of certain desired parts can be checked.

- Shopping for parts

In the case of users looking to print parts that are only available for printing from off-site premises, they can use the app's search function to search for the specific parts they would like to have printed and delivered to their premises. Once said parts have been located, they may be added to users' carts and the order may be confirmed. Users will be given an estimated time of delivery for the products.

- Tracking orders

Through the order tracking functionality, mining operation representatives are able to keep track of their orders and plan and organise mining activities around the expected delivery of said parts. This functionality allows the mining representatives a sense of control as they can constantly check the progress of their orders.

- Viewing database for printable parts

One of the critical points of the design engineering aspect is confirming the printability of an object as mines (especially when the printing process occurs on-site) need to confirm whether the part that is broken can be fixed or reproduced using additive manufacturing means. This can be done by searching for the specific details of the part on the application. If this part's details are not returned, this means that the part should not be reproduced using 3D printing. Examples of these parts are those that are made of material that burns instead of melting when under high temperatures.

Usability Heuristics (design thinking)

The following usability heuristics were prioritised in the design of the application. The application is designed with users that have an above average knowledge with regards to navigating and interacting applications that coordinate the buying and selling of goods. This user segment will consist of users

1. **User Control and Freedom:** To allow users a significant amount of freedom, (restricted to the app permissions they have) the app will offer the user with easy closure and undo and redo options. This is achieved through confirmation pop-up messages, "done" and "cancel" buttons.
2. **Consistency and Standards:** As can be seen by the wireframe, the app will have a consistent colour scheme and consistent fonts and button sizes. This creates a sense of continuity and familiarity for the user while maintaining an appealing aesthetic for the application.

A prototype of the above solution can be found in Appendix C.

Printing Premises

With the hybrid as the chosen solution, the next point of action was to investigate how to implement different ways of achieving the solution's primary focus, which is to conduct most of the printing of spare parts, i.e., roughly 90% of the spare parts required, on-site. To evaluate how attainable, the goal is, the following main factors had to be considered: size and the material of the spare part.

Size

Dave Budge is the CEO of Aurora Labs – a 3D printing company developing 3D printing in the mining industry. In an interview about the printing of spare parts for mines, Dave stated that most clients they had spoken to confirmed that about 90% of the spare parts are within 450x450x450mm in size - (Lempriere, 2023). Many 3D printers, including Aurora machines themselves - (Lempriere, 2023), can print objects of this size. However, it must be noted that these results are specific to clients that this company, Aurora, interviewed. One cannot overlook the fact that other mining companies/sites may require a greater number of spare parts that are larger than 450x450x450mm.

Material

With regards to materials, steel is the primary material used in mining equipment due to its inexpensive, durable, strong and lightweight attributes. Nickel-chromium, iron, and molybdenum are also a part of the most used alloys in 3D printing. Using a technique called Direct Metal Laser Sintering (DMLS), SLM (Selective Laser Melting), and EBM (Electron Beam Melting), all metals can theoretically be 3D printed – (TWI, 2023). However, it must be noted that not all printers can print many different materials. This means that, although it is a great deal less than printing completely on-site, more printers will still be needed on-site to print the different materials than originally planned.

And so, this 90% figure is undoubtedly reachable. The 3D printing technology exists to enable us to reach it. However, it is not reasonable to aim for this 90% figure in all cases and for all mining projects. To reach this target, more printers may be needed on-site to print a greater variety of materials and sizes. This cost may then exceed the cost of printing off-site and transporting the spare part to the mine. And so, it is crucial to weigh up the costs, and estimate the ideal percentage of spare parts to print on-site and off-site for each specific mine. In that way, we best utilize the advantages of the hybrid solutions.

Transportation

After receiving feedback from our sponsors, the project team has decided that the preferred solution to solve the problem of transporting the spare parts to mines, would be the hybrid solution.

The hybrid solution involves the use of trucks (that are outsourced from companies) to transport larger spare parts and drones to transport smaller spare parts.

There are certain steps that can be executed to implement the preferred solution.

Step 1: Assess the transportation needs

The first step would be to evaluate the transportation needs of the mines, including the size and weight of the spare parts that need to be transported, the distance between the mine and the 3D printing premises and the frequency of deliverables.

Step 2: Determine the optimal delivery method

Based on the analysis of transportation needs, the most suitable delivery method for each type of spare part. Large and heavy spare parts are better transported by trucks, while smaller and lighter spare parts can be transported by drones.

Step 3: Develop a logistics plan

Once the delivery method is determined, a logistics plan must be developed that outlines the routes, schedules and delivery points for both trucks and drones. The plan should also include contingency measures in case of unforeseen circumstances.

Step 4: Procure the necessary equipment

To implement the hybrid solution, the necessary transport equipment (such as drones, trucks and other transportation vehicles) must be procured. The equipment must be reliable and of high quality as well as suitable for the transportation needs of the mines

Step 5: Train personnel (if needed)

The personnel responsible for the transportation of the spare parts should receive training on how to operate the equipment, follow the logistics plan, and maintain safety standards.

Step 6: Test and refine the solution

Before implementing the hybrid solution, it should be tested on a small scale to ensure that it works as intended. Any necessary refinements should be made based on the results of the testing.

Step 7: Implement the solution

After testing and refining the solution, it can be implemented on a larger scale. Regular monitoring and evaluation of the solution should be done to ensure that it continues to meet the transportation needs of the mines.

These steps are an extremely helpful guide and starting point to implementing the hybrid solution.

Project Planning & Implementation

Besides ideating solutions to the problems identified in the first part of this document, the project team was also embarking on a journey of project management and employing project management principles and methodologies that fall under the Project Management Body of Knowledge (PMBOK). Below is a detailed view of the undertaking of the project that considers what the project objectives were, who the internal stakeholders were, how the project team went about scheduling project activities and what risks were faced.

Project Objectives

Before ideating the solutions to the problem, the project team first delved into what the project aimed to achieve as knowing this would let the project team know when the project would be seen as being finished, whether it was successful in the end and how time would need to be managed. Here is the list of objectives that were identified:

- The project team had to develop a method of protecting access to the OEM's CAD schematics to ensure that they would not be accessed by unauthorised users.
- They had to develop a method to ensure that 3D-printed spare parts adhere to regulations of quality control.
- They had to develop a solution that would enable on-demand 3D printing of spare parts by high-value industries, OEM's or local service providers.
- They had to develop a solution that would enable secure transportation of spare parts to mines.

- They had to ideate a solution that considered where the spare parts would be printed.

- They had to develop a solution that would keep in mind how the fine-tuning of the 3D printed parts would occur.

Furthermore, after identifying the project objectives, the project team moved on to do an internal stakeholder analysis which would prove to be very useful as knowing the internal stakeholders meant that the project team knew who to direct their questions to as well as who to go to for any clarifications or guidance.

Internal Stakeholder Analysis

In this section we present a Stakeholder Analysis table, that was used to identify and evaluate the stakeholders within our project. These stakeholders were individuals that had an interest or were affected by the project. This table can be found in Appendix E.

Project Scheduling

Project Scheduling was an important aspect of managing this project as this process enabled the timely delivery of the project scope. Having project schedule(s) led to improved productivity and thus a greater and more in-depth understanding of the scope. Project Scheduling was made possible through the following activities.

Product Breakdown Structure

The Product Breakdown Structure is a diagram that offered the project team a clearly defined walkthrough of the main product functions and all the activities that are involved in a hierarchical manner. The Product Breakdown Structure for this project can be found in Appendix F.

Work Breakdown Structure

The Work Breakdown Structure was a vital project management tool that broke down project activities into smaller/atomic tasks and this helped to direct the cost, scope and time factors of a project. The Work Breakdown Structure for this project is found in Appendix G.

Network Diagram

The aim of this network diagram was to showcase the inter relations between activities in a project in a graphical manner using arrows, costs and boxing mechanisms. This can be found in Appendix H.1. A supplementary task table has been added to Appendix Hh2 to understand the different tasks showcased in the network diagram.

Gantt Chart

The Gantt chart helped to visually represent the project plan over time. This diagram can be found under Appendix I.

As described above, project scheduling was a matter of great importance that aided the project team with their time management and provided a structure as to how to get to the finish line. What follows is a detailing of the risk management plan that the project team created to identify risks and to be able to mitigate them.

Risk Management

The success of any project is dependent on how well the project team can anticipate and manage risks that may arise. The risk response plan below, outlined the specific actions that would be taken to mitigate the impact of an identified project risk, were the risk to actualize. The project team also addressed the question of who would be responsible for managing each risk as well as what could trigger the contingency plan if the risk occurred. By following this risk response plan, the project team became better equipped to manage unexpected events.

Risk Response Plan

The risk response plan mapped the identified potential project risks to possible mitigation methods. This plan prepared the team for potential risks and offered them the opportunity to readily respond to issues that presented themselves. The risks were put into three categories: Low risk, Medium risk and High risk. The risk response plan can be found under Appendix J.2 along with its key (Appendix J.1)

Prototyping & Testing

The solution to the defined problem will be a fully-fledged system that will be composed of two main phases with each phase covering critical tasks that are necessary for the realisation of 3D printing on demand for the mining industry. From the identified critical tasks (each outlined thoroughly in the final solution above), only the following were prototyped:

Design Engineering:

In the proposed solution for design engineering, a manual that outlines the necessary steps and procedures that need to be followed in order to ensure that printed parts of high-quality and standard are produced is prototyped. This manual is divided into three sections which include the parts analysis, the actual printing and the postprocessing procedures. The prototype gives an overview of the type of guided content that will be utilised by mining operations and all other relevant individuals when approaching the printing aspect of the system. If the manual is followed thoroughly, then all printed parts are expected to perform well for the quality assurance aspect.

Testing:

Testing the functionality of the manual would require test subjects (expected users of the manual) to undergo a mock printing of a spare part. As alluded to in the constraints and project limitations, the necessary resources to undergo 3D printing are not readily available to the project team, hence the manual's usability could not be tested. However, the manual was designed in an easy to read and understand manner and utilised necessary design principles such as consistent font, clearly structured instructions etc, which will prove beneficial. Continuously, the manual is designed for people aware of the technology of additive manufacturing and as a result, uses terms and terminology that they are familiar with.

Ordering App (An app design):

The ordering application will primarily be responsible for coordinating the ordering of spare parts and ensuring that users are able to keep track of their orders. The design application is outline in Appendix G. This design maximises usability and user navigation. Similarly, due to the identified limitations and constraints, the application could not be deployed to testing but its focused design (with a detailed reference to design principles) ensures a design tailored to its users.

Challenges and Limitations

Upon coming to the end of the project, the project team reflected on the challenges that they faced and thought about what they could have done differently. The project team also reflected on any limitations that they came across during the project. The challenges and limitations are listed below:

Limitations

Below we have provided some points that addresses the limitations our team faced during the project.

1. **Lack of prior knowledge**: One of the limitations that we have experienced involves the lack of knowledge that we had pertaining to the concepts involved in the project. These concepts include design engineering, 3D printing and blockchain technology. Knowing this information before starting the project, would have allowed us to understand the requirements and constraints of the project better.
2. **Limited industry expertise**: The other limitation we experienced involves the lack of interaction with experts in the industry. It would have been better for us to have engaged more with industry experts to gain a deeper understanding of the field and learn from their experience. This would have helped us identify potential issues with our solutions, and the opportunities thereof, earlier in the project.
3. **Delayed questions and scope understanding**: We realized that we took longer than necessary to ask important questions and fully understand the scope of the project. This caused delays and unnecessary complexity to the project.

Challenges

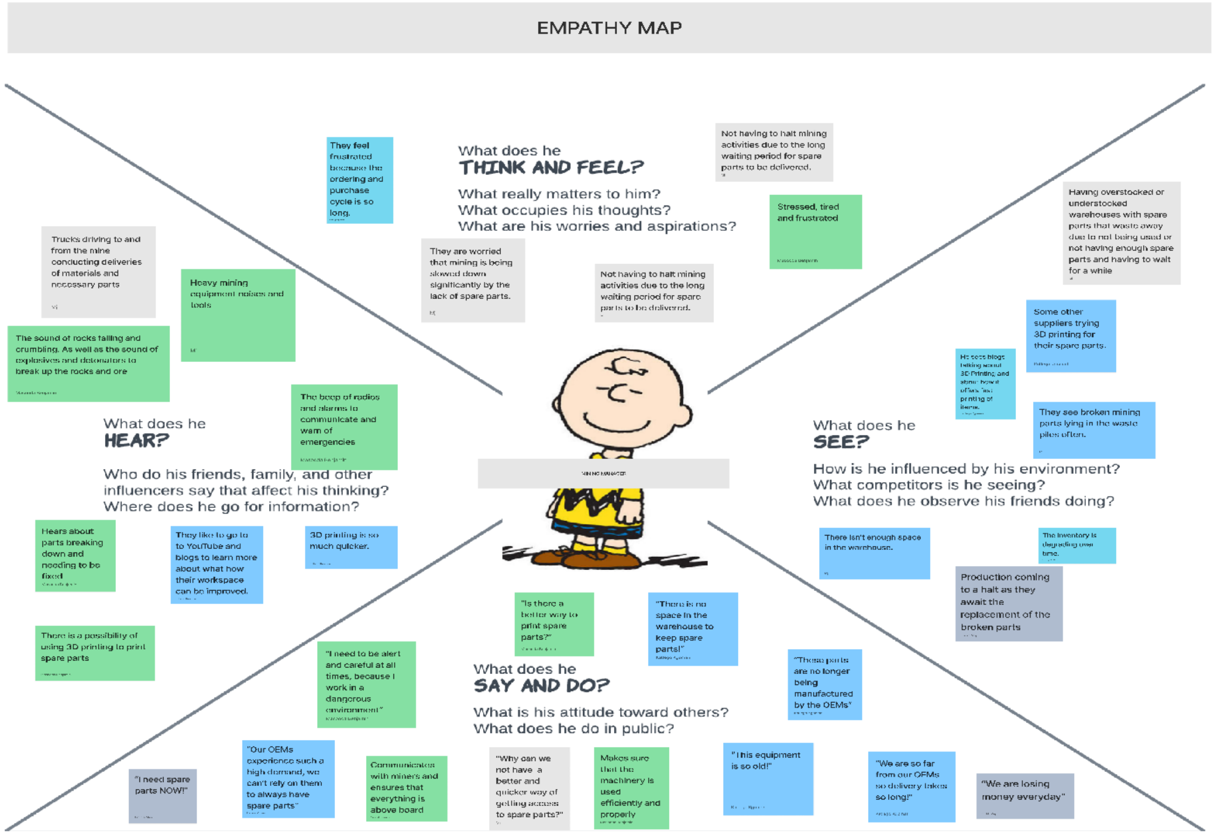
Below we have provided some points that address the challenges that our team faced during the project.

1. **Complex problem statement:** The project has many different aspects, including the 3D printing premises, transportation of spare parts (from the printer to the mine), quality assurance of spare parts, IP protection and design engineering, each of which presented unique challenges. As a team, we had to work hard to develop solutions that addressed each of these aspects while maintain coherence and integration across the project.
2. **Time management:** Our sponsors were not based in Cape Town, which made scheduling meetings and communication a challenge at times. We had to ensure that we used our time efficiently to make the most of our limited opportunities for collaboration and feedback.
3. **Lack of knowledge:** We faced challenges due to our limited knowledge and experience with some of the complex topics (explained in the first point) involved in the problem statement. We had to conduct extensive research and seek our expert guidance to develop a comprehensive understanding of these topics.
4. **Time constraints:** We had very little time to conduct comprehensive research and develop effective solutions for the project. This made it challenging to balance the need for speed with the need of quality and accuracy.
5. **External stakeholder delays:** We experienced challenges with regards to finding the time to meet, and contact, some external stakeholders. This made it difficult for the project team to gain the knowledge and perspective from a professional in the field.

Appendices

Appendix A: Empathy Map

A clearer view of the empathy map can be found here.



EMPATHY MAP

MINING MANAGER

What does he
THINK AND FEEL?

What really matters to him?
What occupies his thoughts?
What are his worries and aspirations?

They feel frustrated because the ordering and purchase cycle is so long.

They are worried that mining is being slowed down significantly by the lack of spare parts.

Not having to halt mining activities due to the long waiting period for spare parts to be delivered.

Not having to halt mining activities due to the long waiting period for spare parts to be delivered.

Stressed, tired and frustrated

Having overstocked or understocked warehouses with spare parts that waste away due to not being used or not having enough spare parts and having to wait for a while

What does he
HEAR?

Who do his friends, family, and other influencers say that affect his thinking?
Where does he go for information?

Trucks driving to and from the mine conducting deliveries of materials and necessary parts

Heavy mining equipment noises and tools

The sound of rocks falling and crumbling. As well as the sound of explosives and detonators to break up the rocks and ore

The beep of radios and alarms to communicate and warn of emergencies

Hears about parts breaking down and needing to be fixed

They like to go to to YouTube and blogs to learn more about what how their workspace can be improved.

3D printing is so much quicker.

There is a possibility of using 3D printing to print spare parts

What does he
SEE?

How is he influenced by his environment?
What competitors is he seeing?
What does he observe his friends doing?

Some other suppliers trying 3D printing for their spare parts.

He sees blogs talking about 3D Printing and about how it offers fast printing of items.

They see broken mining parts lying in the waste piles often.

There isn't enough space in the warehouse.

The inventory is degrading over time.

Production coming to a halt as they await the replacement of the broken parts

What does he
SAY AND DO?

What is his attitude toward others?
What does he do in public?

"Is there a better way to print spare parts?"

"There is no space in the warehouse to keep spare parts!"

"These parts are no longer being manufactured by the OEMs"

"I need to be alert and careful at all times, because I work in a dangerous environment"

"I need spare parts NOW!"

"Our OEMs experience such a high demand, we can't rely on them to always have spare parts"

Communicates with miners and ensures that everything is above board

"Why can we not have a better and quicker way of getting access to spare parts?"

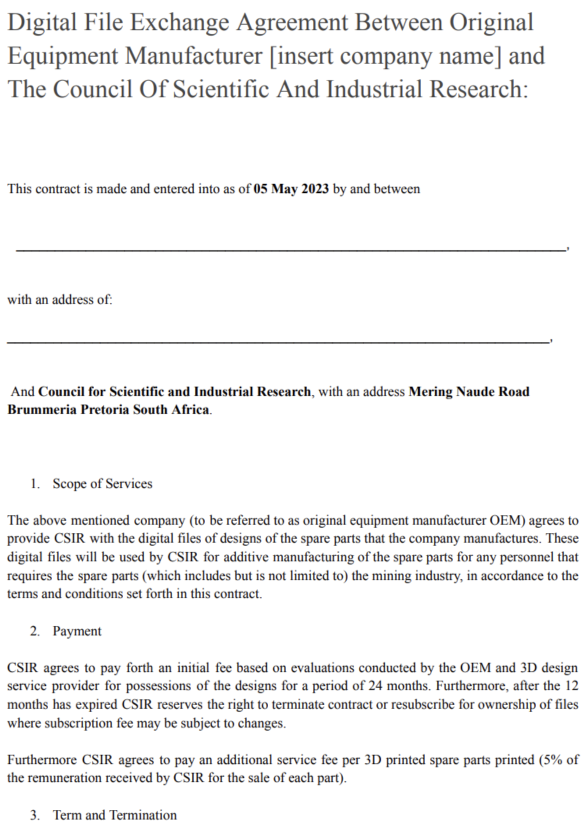
Makes sure that the machinery is used efficiently and properly

"This equipment is so old!"

"We are so far from our OEMs so delivery takes so long!"

"We are losing money everyday"

Appendix B: Agreement



Digital File Exchange Agreement Between Original Equipment Manufacturer [insert company name] and The Council Of Scientific And Industrial Research:

This contract is made and entered into as of **05 May 2023** by and between

____,

with an address of:

____,

And **Council for Scientific and Industrial Research**, with an address **Mering Naude Road Brummeria Pretoria South Africa**.

1. Scope of Services

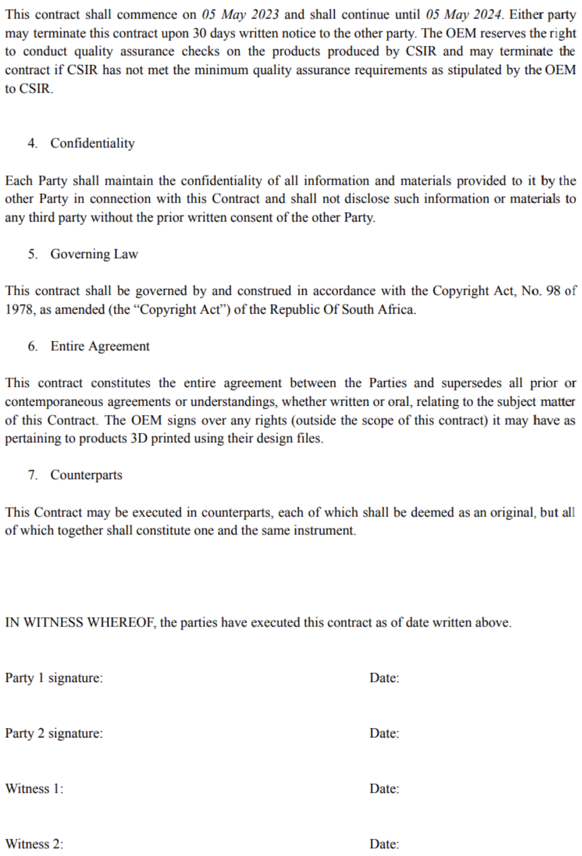
The above mentioned company (to be referred to as original equipment manufacturer OEM) agrees to provide CSIR with the digital files of designs of the spare parts that the company manufactures. These digital files will be used by CSIR for additive manufacturing of the spare parts for any personnel that requires the spare parts (which includes but is not limited to) the mining industry, in accordance to the terms and conditions set forth in this contract.

2. Payment

CSIR agrees to pay forth an initial fee based on evaluations conducted by the OEM and 3D design service provider for possessions of the designs for a period of 24 months. Furthermore, after the 12 months has expired CSIR reserves the right to terminate contract or resubscribe for ownership of files where subscription fee may be subject to changes.

Furthermore CSIR agrees to pay an additional service fee per 3D printed spare parts printed (5% of the remuneration received by CSIR for the sale of each part).

3. Term and Termination



This contract shall commence on *05 May 2023* and shall continue until *05 May 2024*. Either party may terminate this contract upon 30 days written notice to the other party. The OEM reserves the right to conduct quality assurance checks on the products produced by CSIR and may terminate the contract if CSIR has not met the minimum quality assurance requirements as stipulated by the OEM to CSIR.

4. Confidentiality

Each Party shall maintain the confidentiality of all information and materials provided to it by the other Party in connection with this Contract and shall not disclose such information or materials to any third party without the prior written consent of the other Party.

5. Governing Law

This contract shall be governed by and construed in accordance with the Copyright Act, No. 98 of 1978, as amended (the "Copyright Act") of the Republic Of South Africa.

6. Entire Agreement

This contract constitutes the entire agreement between the Parties and supersedes all prior or contemporaneous agreements or understandings, whether written or oral, relating to the subject matter of this Contract. The OEM signs over any rights (outside the scope of this contract) it may have as pertaining to products 3D printed using their design files.

7. Counterparts

This Contract may be executed in counterparts, each of which shall be deemed as an original, but all of which together shall constitute one and the same instrument.

IN WITNESS WHEREOF, the parties have executed this contract as of date written above.

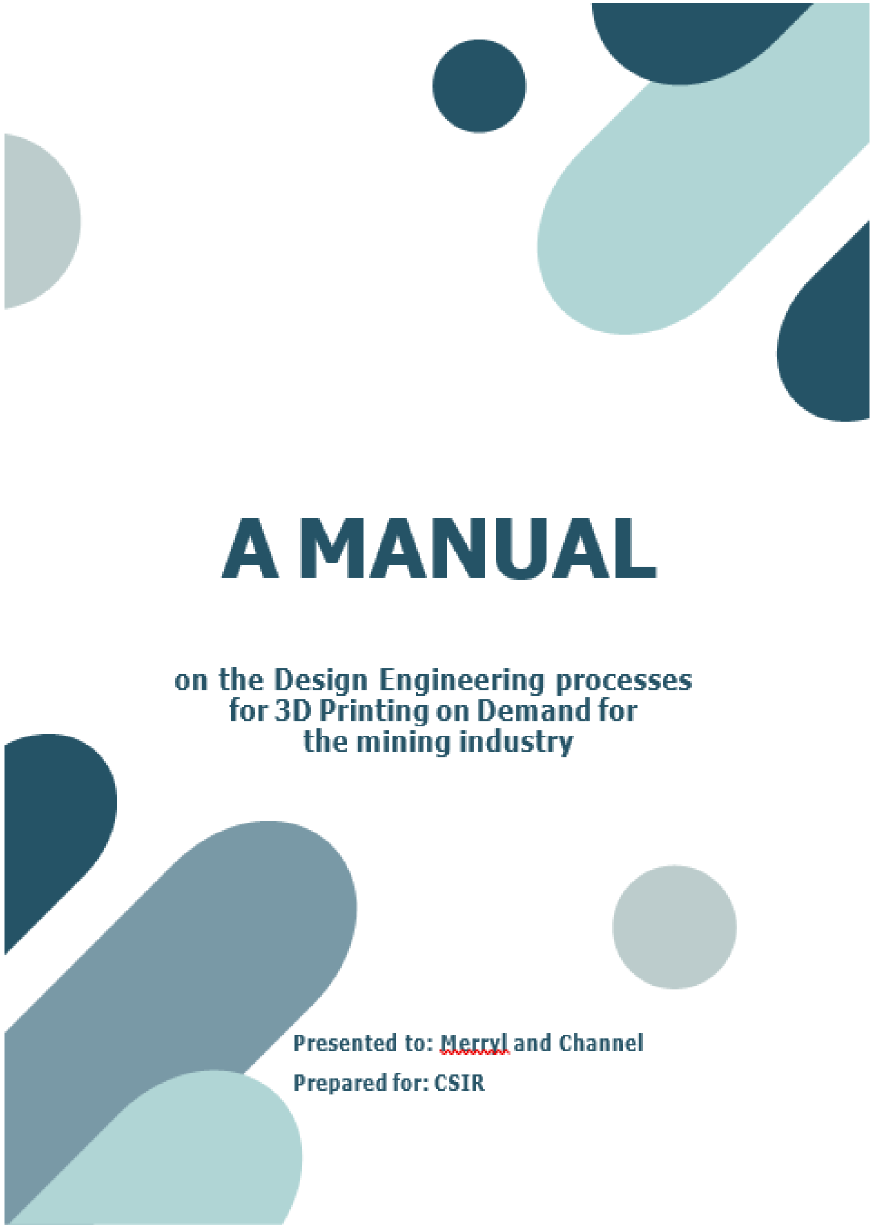
Party 1 signature: Date:

Party 2 signature: Date:

Witness 1: Date:

Witness 2: Date:

Appendix C: “How to” manual



A MANUAL

on the Design Engineering processes
for 3D Printing on Demand for
the mining industry

Presented to: Merryl and Channel
Prepared for: CSIR

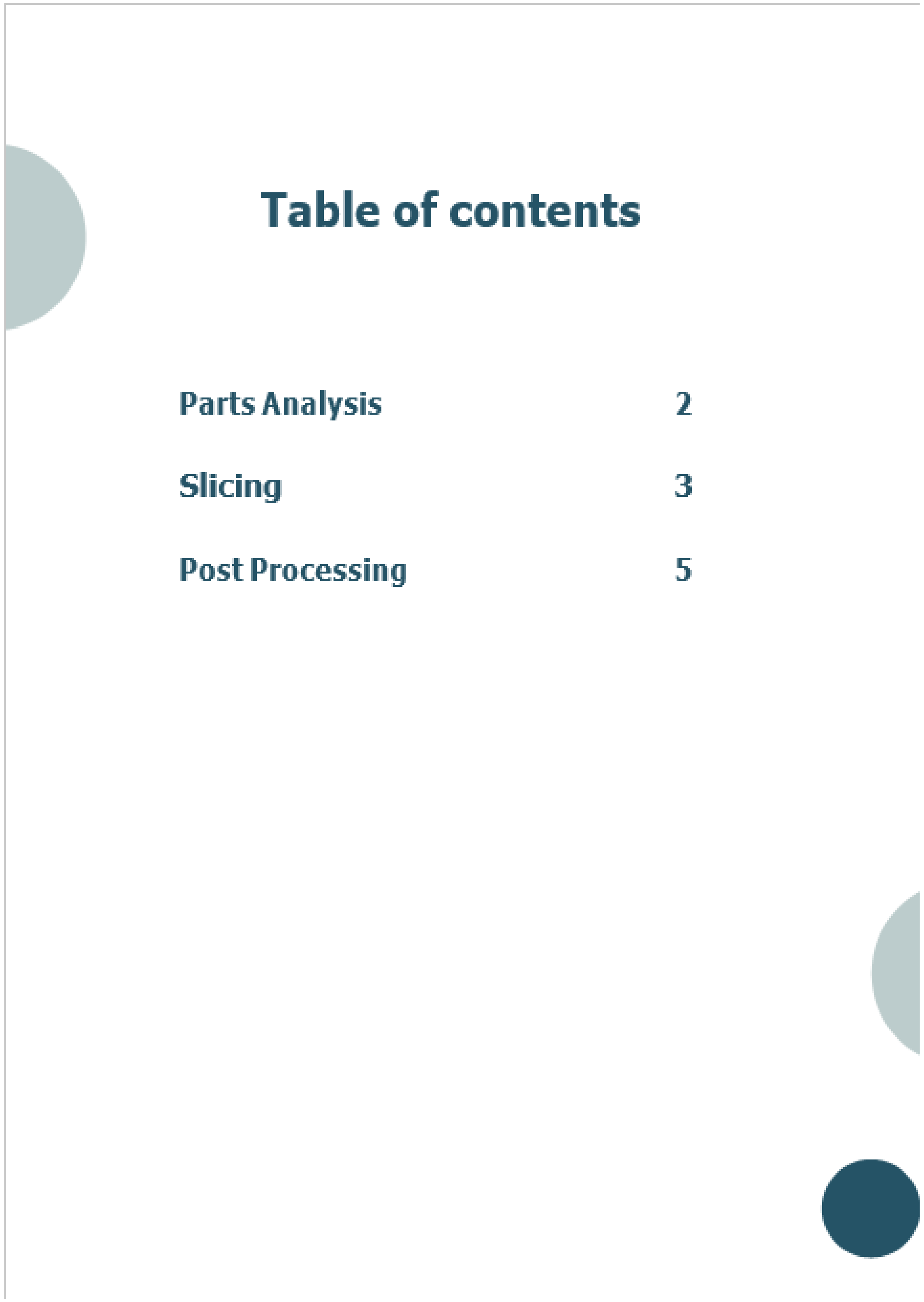


Table of contents

Structure

1 Part Analysis

In the event of a broken part, operations will need some way of determining whether the broken part is suitable for 3D printing or not. Additive Printing proposes many advantages, however, there are some parts, with a primary focus in the mining industry, that are not 3D printable. Operation leaders will need a way to accurately identify these products.

The printing process contains the following steps, applicable to both onsite and offsite printing facilities, unless otherwise stated.

1. Retrieval of CAD files from OEMs
2. Slicing processes

2 Slicing

3 Post Processing

The processes that are absolutely necessary to ensure a proper working and strong product

01 Part Analysis

This section will highlight the steps to be followed when assessing a products viability for 3D printing. This is necessary in order to ensure that:

- Only parts viable for additive manufacturing are printed. This will prevent the changes of wasted resources (funds, time and skill) and deploying dysfunctional parts
- Only objects of suitable material and size are printed (e.g. materials that burn instead of melting under high temperatures are not suitable for 3D printing use)

Process

- Ensure that the CSIR app is downloaded and that the relevant mining representative (e.g. Equipment Manager, Stock Controller) has set up an account on the app and has registered the mine as a client.
- On the CSIR application, use the search button to search the name ofthe product you would like to 3D print
- If the product is suitable for 3D printing, it will appear as one of the results and you will be able to view product details and where to place an order for a 3D printed copy
- Conversely, the product will not be present in the database meaning it is not 3D printable
- A request to check for product viability may be made or the product may be ordered straight from the OEM

02 Slicing

Slicing is a necessary step that translates CAD files into instructions that are perceptible by the 3D printer in the form of geometric code. This process is necessary to ensure that the printed objects are of great quality and make use of the best time and resources available. By optimising the different functionalities of slicing software, parts are printed with the best quality and functionality. This is because the manner in which parts are printed has a great impact on their outcome. The following are the **Slicing** steps or aspects that need to be considered.

Printing Techniques

Selective Laser Melting (SLM)

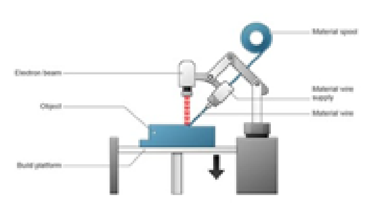
Selective Laser Melting is the desired slicing technique to be used due to its dependability with printing high quality metal 3D printed parts. SLM offers benefits such as great precision, the ability to print complex models and a wide range of build volumes. To use this technique, weather on-site or off-site, institutions need to ensure that:

- there are trained professionals to operate the machines with the SLM slicing technique
- the intricate process is followed thoroughly in order to wield desired results
- SLM machines and the materials used for the printing process are expensive and need to be well managed

Directed Energy Deposition (DED)

This technique offers both the printing of new parts and the refining of damaged parts. Like SLM, it is most ideal for the precise printing of metal parts through using powder or wire.

- The ability to repair damaged metal offers multipurpose printer functionality
- This technique offers the function to print objects ofvarying materials.
- Offers the ability to print objects of multiple sizes



DED Manufacturing Process using an Electronic Beam

---

02 Slicing Cont.

Slicing Software

Slicing software is utilised to convert a 3D model (CAD file in an STL file format) divide the 3D model to be printed into instructions understandable by a specific printer in the form of Geometric Code. The model is divided into layers which are optimised to ensure reliably printed objects.

IceSl Slicing Software

IceSL
modeler and slicer

This is an advanced software that offers professional slicing and modelling functionalities. The IceSl website offers tutorials, guidelines and videos to assist users with the printing process. Features include advanced bridge support, progressive refills and per layer settings.

Necessary documentation and cheat sheets can be found in on the software's website.

Extra Precautions

- Use of multi-axis machinery
- Use of finite element analysis to enable topology optomisation
- Repetition of printing procedures to ensure that products come out printed

03 Post Processing

After the printing of the desired parts, a dedicated team of professionals is required to complete the following post processing activities in order to ensure that the printed products come out in optimal form.

Support Removal

Surface Smoothing

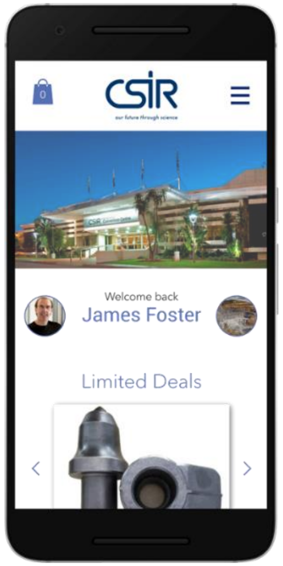
Parts Strengthening

Adding Part Functionality

Aesthetic Finishing

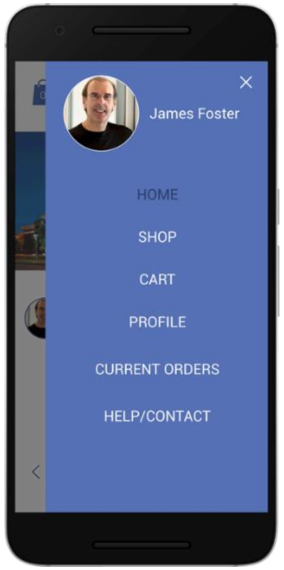
Appendix D: Wireframe for the CSIR Application

The following is a wireframe of the CSIR application developed for the purpose of placing orders for 3D printed parts.



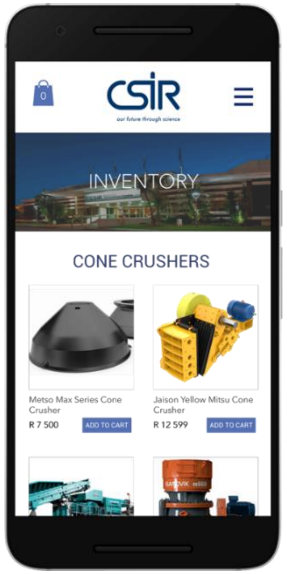
Landing Page

This is the first page that users are directed to. This showcases the user signed in on the app and multiple limited deals or specials. The page has easy and familiar navigation and users are even able to view the contents of their carts.



Menu Page

The menu page outlines the different pages that the application offers, allowing the user to navigate between the multiple functionalities of the app.



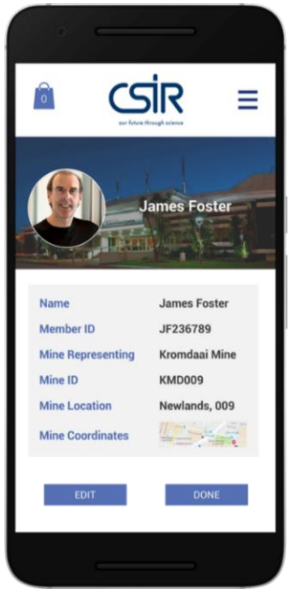
Inventory Page

This page has all the inventory and available products to be printed

Metso Outotec MX™ Series cone crushers are ideal for secondary, tertiary and quaternary crushing stages in hard and soft rock applications. The patented multi-action technology is a revolutionary way to optimize crusher's setting and wear compensation in real time.

Product Page

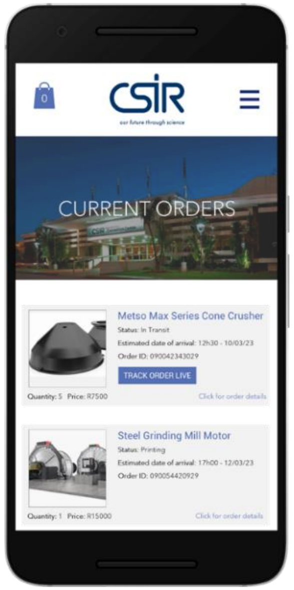
This page offers a concise product description and gives information on the pricing and details of a product while enabling the user to add a product to their cart and place an order



Name	James Foster
Member ID	JF236789
Mine Representing	Kromdaai Mine
Mine ID	KMD009
Mine Location	Newlands, 009
Mine Coordinates	

Profile Page

The profile page gives a comprehensive view of a user's details including the main they are representing, the said mine's geographical location, ID and name



Metso Max Series Cone Crusher
Status: In Transit
Estimated date of arrival: 12h30 - 10/03/23
Order ID: 090042343029
Quantity: 5 Price: R7500

Steel Grinding Mill Motor
Status: Printing
Estimated date of arrival: 17h00 - 12/03/23
Order ID: 090054420929
Quantity: 1 Price: R15000

Current Orders

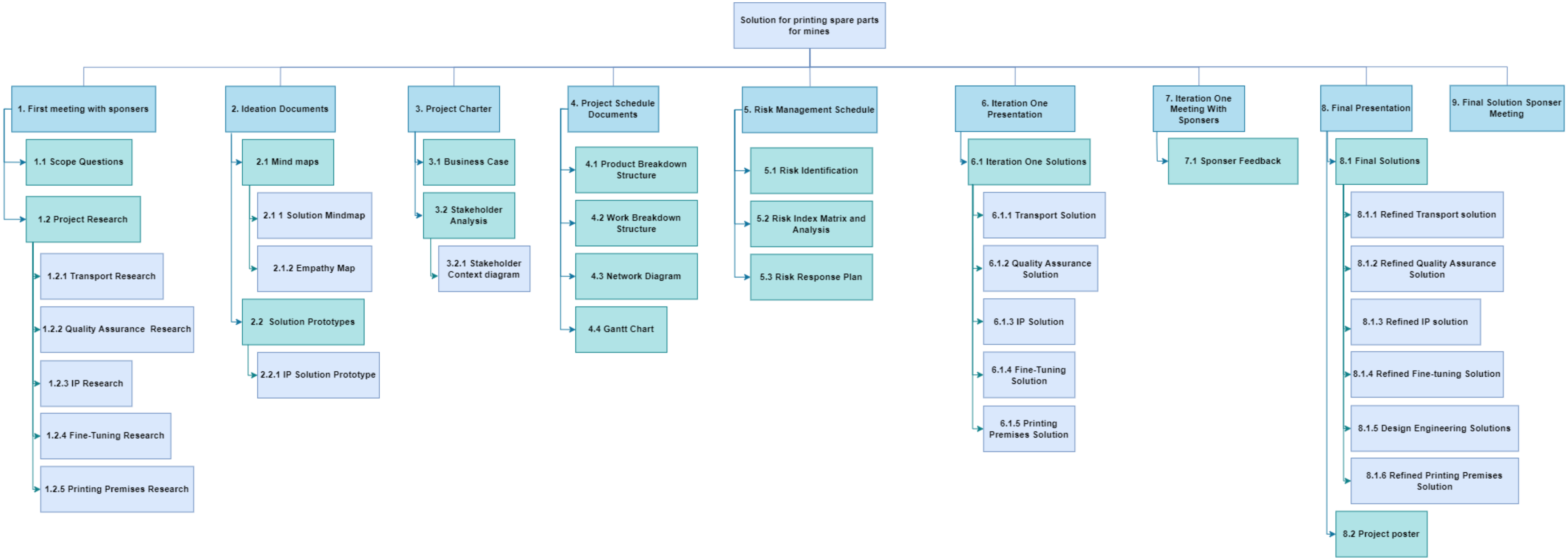
This page shows the current awaited for orders.

Appendix E: Internal Stakeholder Analysis Table

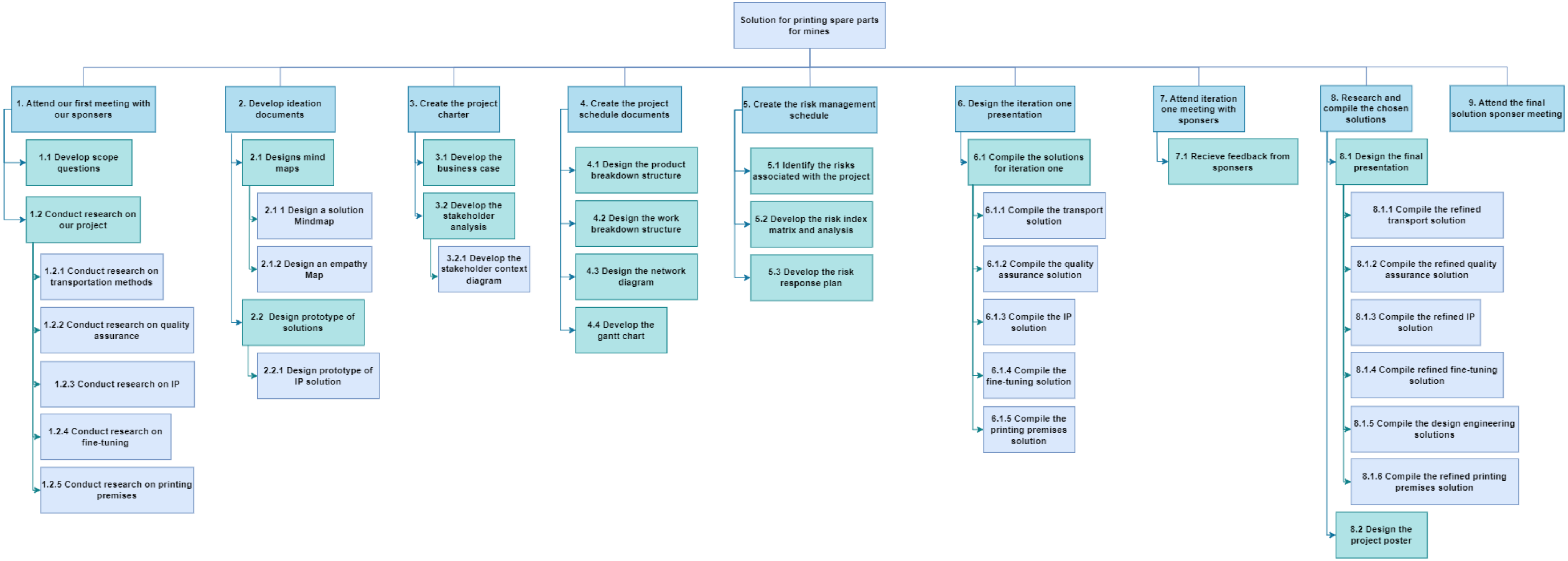
Stakeholder	**Contact information**	**Role on the project**	**Level of influence**	**Level of interest**	**Engagement strategy**
CSIR (Project Sponsors)	**Merryl Ford** mford@csir.co.za 063 680 6441 Chanel Schoeman CMSchoeman@csir.co.za	CSIR (represented by Merryl Ford) presented the project problem and scope to the project team. They were the client, and they played a vital role in determining the project direction.	High	High	Bi-weekly meetings over MS Teams
Project supervisors	Gwamaka Mwalemba gt.mwalemba@uct.ac.za	He provided the project with the project and offered guidance during the first iteration of the project solutions.	High	High	Monthly meetings in person
Project Mentor	Chloe Walt WLTCHL002@myuct.ac.za	She provided advice to project team with during the planning and ideation phases of	High	High	Bi-weekly meetings in person

		the project and offered her help whenever it was needed.			
Project Team	Emihle May MYXEMI001@myuct.ac.za Kane Gibson GBSKAN001@myuct.ac.za Katlego Kgomari KGMKAT002@myuct.ac.za Modjadji Francis FRNMOD001@myuct.ac.za Masooda Benjamin BNJMAS003@myuct.ac.za	They have been involved in the planning and ideation of the solutions for the problem statement. They have also been involved in the prototyping of the solution.	High	High	Meeting as often as possible throughout the duration of the project.

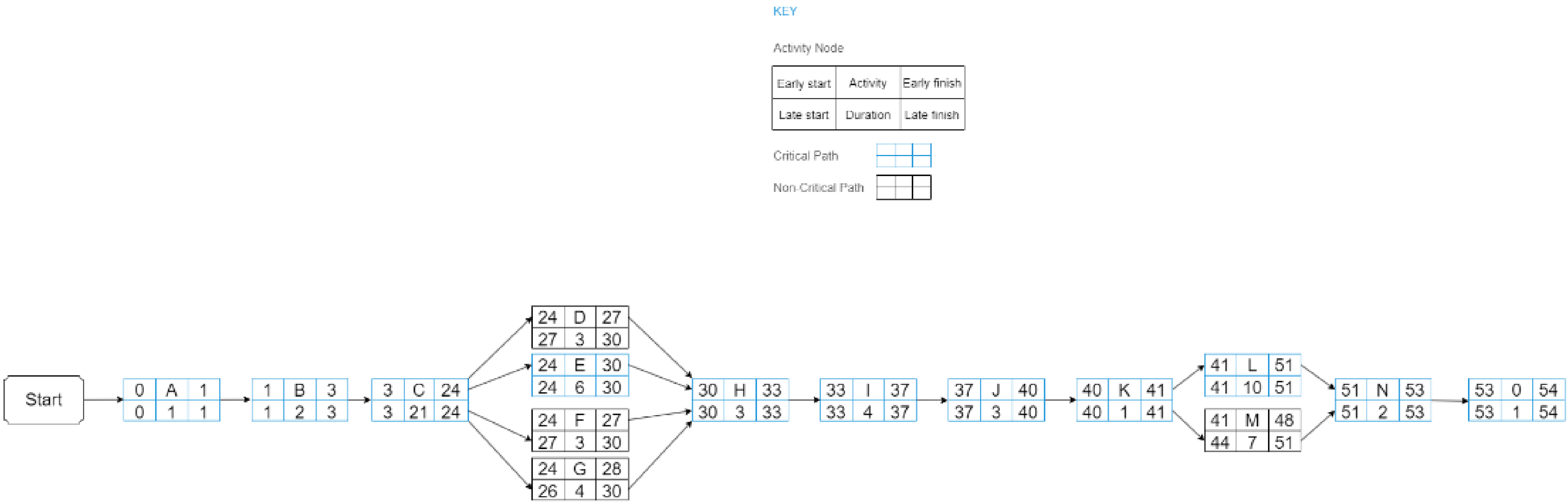
Appendix F: Product Breakdown Structure



Appendix G: Work Breakdown Structure



Appendix H.1: Network Diagram

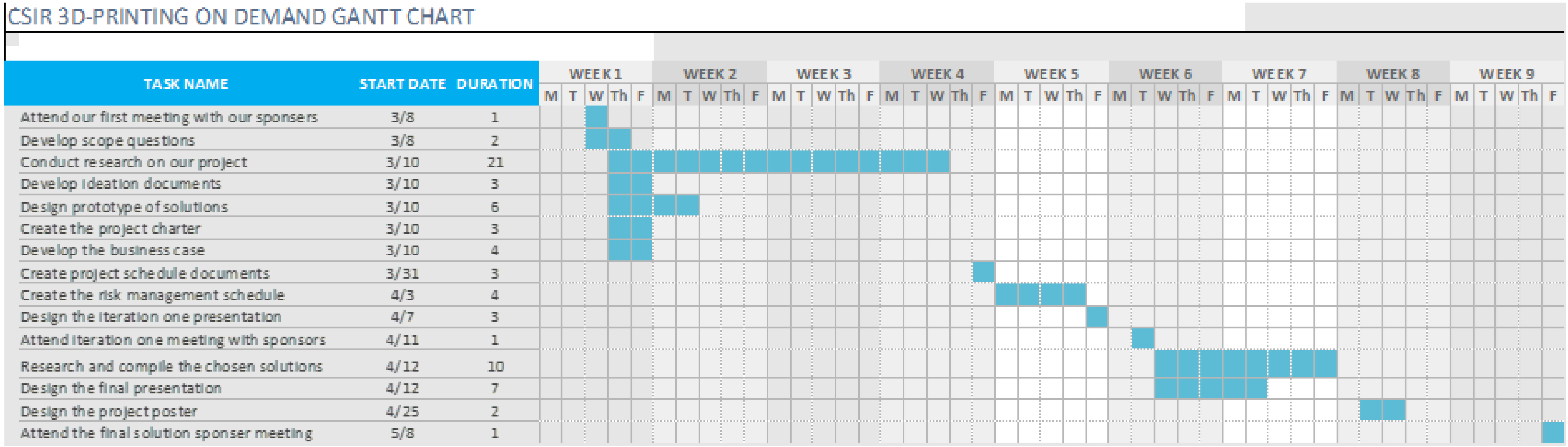


Sum of critical path: 1 + 2 + 21 + 6 + 3 + 4 + 3 + 1 + 10 + 2 + 1 = 54 days

Appendix H.2: Task Table

Task ID	Task Description	Predecessor Task(s)	Task Duration
A	Attend our first meeting with our sponsors	None	1 day
B	Develop scope questions	A	2 days
C	Conduct research on our project	B	21 days
D	Develop ideation documents	C	3 days
E	Design prototype of solutions	C	6 days
F	Create the project charter	C	3 days
G	Develop the business case	C	4 days
H	Create project schedule documents	D, E, F, G	3 days
I	Create the risk management schedule	H	4 days
J	Design the iteration one presentation	I	3 days
K	Attend iteration one meeting with sponsors	J	1 day
L	Research and compile the chosen solutions	K	10 days
M	Design the final presentation	K	7 days
N	Design the project poster	L, M	2 days
O	Attend the final solution sponsor meeting	N	1 day

Appendix I: Gantt Chart



CSIR 3D-PRINTING ON DEMAND GANTT CHART

TASK NAME	START DATE	DURATION
Attend our first meeting with our sponsers	3/8	1
Develop scope questions	3/8	2
Conduct research on our project	3/10	21
Develop ideation documents	3/10	3
Design prototype of solutions	3/10	6
Create the project charter	3/10	3
Develop the business case	3/10	4
Create project schedule documents	3/31	3
Create the risk management schedule	4/3	4
Design the iteration one presentation	4/7	3
Attend iteration one meeting with sponsors	4/11	1
Research and compile the chosen solutions	4/12	10
Design the final presentation	4/12	7
Design the project poster	4/25	2
Attend the final solution sponser meeting	5/8	1

Appendix J.1: Risk Response Plan key

Rank	Description
1	High Risk
2	Medium Risk
3	Low Risk

Appendix J.2: Risk Response Plan

No	Rank	Description	Probability	Impact	Category	Cause	Triggers	Owner	Mitigation	Contingency	Status
R1	3	A project team member could have fallen ill leading to a delay in deliverables and project time being affected.	Medium	Low	Team members	Spontaneous due to numerous factors.	Once it happened often (member getting sick) and 40% of project tasks fell behind by two days.	Project Manager and team	Practised good health practises as a team such as exercising.	PM (Project Manager) took on tasks of ill individual or delegated to the rest of team.	Green
R2	1	Project scope was not properly defined at the start and additional work was done than required (scope creep).	High	High	Project planning	Inadequate research was on the project topic.	Team realised after first iteration that there was much more that needed to be done or they went beyond scope of project.	PM	Spend thorough time understanding and researching the problem statement and clearly define in business case. Implore	Redefine scope of project and set sprints to achieve new goals.	Red

									project agile methods		
R3	1	Inexperience or inadequate information about complex technologies involved in the project (3D printing, transport, IP protection, fine tuning methods)	High	High	Project scope	Lack of research or conducting interviews with stakeholders as well as confusion.	When the planning stage (in terms of finding the solution) exceeded beyond two days than the scheduled planning time.	Project team	Conduct as much research as possible, enquire from the lecturer about complexities of technology.	Met again with sponsors and tried to understand technologies that they use and tried to meet with experts in field to understand problem.	Amber
R4	1	Lack of financial knowledge of project may have led to an impractical solution.	High	High	Technical	CSIR did not share with team members proposed budget for project.	Sponsor expressed that proposed solutions were not possible to implement after the iteration one meeting.	PM	Conducted feasibility assessment on solution.	Performed cost benefit analysis on each new proposed solution and cost of implementation.	Amber
R5	3	There could have been conflict amongst members in the team which could have hindered project productivity, resulting in the project not being completed on time and within scope.	Low	Medium	Team members	Responsibilities not fulfilled by team members. Members may have never worked together before.	Constant arguments occurred between members and exceeded the time given, for finding solutions, by three days	Project Team	Implemented good internal communication and held members accountable.	Involve the assistance of project mentors.	Green

R6	2	Given that the team members are new to the project management, they may not have applied the project management strategies well enough	Medium	Medium	Team members	Poor implementation of theory learnt in real life.	If more than 30% of the project deliverables are not being completed on time.	Project Team	Constantly refer to experience in projects and lessons to keep track of all that is needed.	Familiarise the team with project management strategies Refer to other projects using the same strategy as a guide.	Green
R7	2	The first iteration of solutions may not have been well-received by project sponsors.	Low	High	Project Solutions	Inadequate research may have been done on the project topic.	Once the project solutions were not received well by project sponsors during the first iteration meeting.	Project Team	Maintained proper communication with sponsors to ensure that the scope was well understood, and thorough research could conducted	Conducted further research and worked on different solutions after gaining feedback from sponsors.	Green
R8	2	The fact that the project team was in a different province than the sponsors may have lead to poor communication.	Medium	High	Poor communication	The CSIR was based in a different province than the project team	If there was an increase in the number of missed deadlines or miscommunications between the project team and sponsors	Communication Facilitator	Communicated as frequently as possible with the project sponsors	Tried other methods of contacting the sponsors and consulted the project mentor if other contact	Green

							by more than 25% compared to the previous weeks.		and sent follow up emails as reminders if the sponsor had not responded to the initial email.	methods were not working out.	
R9	2	Conducting proceedings between stakeholders and project members online meant a lack of onsite experience which could have lead to misunderstandings about aspects of the scope and project.	High	Low	Project Scope	The CSIR was based in Pretoria and so that was where the Project Sponsors were situated. UCT students (project members) were unable to travel there.	After Iteration 1, Project Sponsors pointed out that certain factors were not considered when creating the solution.	Communication Facilitator.	Frequent communication (asking questions and for clarification) with Project Sponsors meant that the team was able to find out about any intricacies that were missed by not having hadsite experience.	If it was found that a gap in knowledge meant that the solution produced was unsatisfactory, the communication facilitator could have renegotiated for a new project due date to allow for the missing details to be accounted for in the final solution.	Green
R10	2	The lack of a project leader could have led	Low	High	Project Scheduling	Nobody took the initiative to	Once the due date of the first deliverable was missed, it meant	All Project Team	Elected a Project Leader at the very	Negotiated a week to catch up on the first deliverable and	Green

		to disorganisation and wasting time.				become project leader.	that scheduling and organisation had not occurred as it should have.	Membe rs	beginning of the project (this was declared in the project charter).	continued from there.	

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