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TRIZ inspired design guidelines for remanufacturing using additive manufacturing

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TRIZ inspired design guidelines for remanufacturing using additive manufacturing

by

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

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GLOSSARY OF TERMS

AM	-	Additive Manufacturing
ABS	-	Acrylonitrile butadiene styrene
CAD	-	Computer Aided Design
CLIP	-	Continuous Liquid Interface Production
CGDS	-	Cold Gas Dynamic Spray
CNC	-	Computerized Numerical Control
DED	-	Direct Energy Deposition
DFA	-	Design for Assembly
DFAM	-	Design for Additive Manufacturing
DFD	-	Design for Disassembly
DFR	-	Design for Reassembly
DFX	-	Design for X
DfRem	-	Design for Remanufacturing
DLD	-	Direct Laser Deposition
DLM	-	Direct Laser Melting
DMLS	-	Direct Metal Laser Sintering
EOL	-	End of Life
EBM	-	Electron Beam Melting
FDM	-	Fused Deposition Modeling
GTAW	-	Gas Tungsten Arc Welding
IR	-	Independent Remanufacturer

LBM	-	Laser Beam Melting
LENS	-	Laser Engineered Net Shaping
LDD	-	Laser Direct Deposition
LMD	-	Laser Metal Deposition
LS	-	Laser Sintering
OEM	-	Original Equipment Manufacturer
PBF	-	Powder Bed Fusion
PFS	-	Powder Feed System
RemPro	-	Remanufacturing Property matrix
RP	-	Rapid Prototyping
SD	-	Secure Digital
SLA	-	Stereolithography
SLM	-	Selective Laser Melting
TRIZ	-	Theory of Inventive Problem Solving
TIPS	-	Theory of Inventive Problem Solving

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ABSTRACT

Remanufacturing is the process of turning used products into new ones in terms of quality, functionality, and aesthetics with relatively lower product price. To make the process of remanufacturing easier, certain changes may be required in the design of a remanufactured product. The advent of additive manufacturing has opened new opportunities for the design for remanufacturing with an increase in the feasibility of various product design options for remanufacturing. Although there are design guidelines scattered across literature, a set of design rules or guidelines that facilitate remanufacturing using additive manufacturing is not clearly provided in the extant literature. To fill this void, this research focuses on building a set of design guidelines based on a TRIZ matrix to solve conflicting problems or issues on design for remanufacturing. The proposed TRIZ matrix facilitates necessary design guidelines for remanufacturing using additive manufacturing. A case study is provided to elaborate on the application of the design guidelines derived from the proposed methodology. This study develops a user friendly TRIZ tool which will help identify all the parameters that need to be considered for remanufacturing and provides feasible solutions to successfully remanufacture a product. This tool will be of great use to industries and designers trying to design parts for remanufacturing.

CHAPTER 1

INTRODUCTION

1.1 Motivation

In recent times, the pollution caused due to excessive usage of materials and resources, emphasis is being put on the idea of "enough consumption." Terms such as reuse, repair, refurbish and recycle have become synonymous with green consumption and sustainability as they help reduce waste and reduce the production of more than required. In this context, remanufacturing is another term that is gaining rapid popularity. "Remanufacturing is an industrial process that turns used products into products with the same quality, functionality, and warranty as new products" (Giuntini et al., 2003). Just like any manufacturing process, remanufacturing involves a set of processes/steps such as disassembly, cleaning, inspection, reconditioning/repair, reassembly and final testing that the products need to go through. Of these processes, repair or reconditioning is the part that poses a major challenge because it often requires skilled labor to repair the part and make it look like new.

Traditionally, welding has been used to repair damaged parts, but it is not ideal for damaged 3D structures as it creates a non-uniform surface microstructure from the filler materials and base material leading to poor bonding between the filler material and damaged part (Ding et al., 2015). With the latest developments the field of additive manufacturing, depositing metal to form a 3D structure has become possible. Several metal additive manufacturing techniques have come to play a major role in the remanufacturing industry. Selective laser melting (SLM), electron beam melting (EBM), direct energy deposition (DED), laser engineered net shaping (LENS), cold gas dynamic spray (CGDS), etc. are some of the current metal AM techniques that could potentially be used for remanufacturing. Wilson et al. (2014) have used the LENS process to remanufacture turbine blades and analyzed its environmental impact while Lee et al. (2007) used CDGS process to repair damaged mold surface. CDGS is another new AM technique that is being researched intensively for remanufacturing (Hu et al., 2005; Zwolinski et al., 2006).

Despite the technical advances to make remanufacturing of parts economically viable, there are still many barriers to it. Lack of awareness among customers of what a remanufactured product means, having an efficient remanufacturing process in place – including for disassembling and reassembling apart, access to technology and skilled labor required for remanufacturing, effective collection of used parts and sometimes, reluctance of OEMs to remanufacture are a few to start with (Matsumoto et al., 2016). Previous research reveals that many of the barriers that occur during remanufacturing can be mitigated through proper decisions made during the design process (Matsumoto et al., 2016). Product design plays a major role in making remanufacturing of that product more efficient and cost-effective (Nasr et al., 2006; Steinhilper et al., 1998). This emphasizes the need for design for remanufacturing. Design for remanufacturing has been defined as a "combination of design processes whereby an item is designed to facilitate remanufacture" (Charter et al., 2008). There is a good amount of literature focusing on developing a set of design guidelines to facilitate remanufacturing (Matsumoto et al., 2016; Charter et al., 2008; Ijomah et al., 2007; Ijomah et al., 2007a; Sundin et al., 2008). A different set of design guidelines might be required at each step-in remanufacturing such as design for disassembly, design for cleaning, and design for inspection, etc. This has been achieved to some extent by Sundin and colleagues who studied product properties such as ease of handling, separating, access that are preferable for each step of the remanufacturing process (Sundin et al., 2004).

Most of these guidelines are directional and qualitative in nature and collectively present a comprehensive and complementary insight into steering a design toward higher remanufacturability (Matsumoto et al., 2016). However, this approach to DfRem has also been criticized as being lengthy and overly-daunting, as it is impossible for designers to consider all of these criteria simultaneously, and some of the remanufacturing design requirements even intrude on traditional design (Zwolinski et al., 2006). There is also not much literature describing the design guidelines for remanufacturing using additive manufacturing, given that AM could be the potential future of remanufacturing.

Overall, several opportunities exist to make remanufacturing feasible. There is a great potential for AM techniques to be used for remanufacturing and repair of parts, which could not be achieved before the advent of AM. Designing a product keeping its end of life in mind and making minor design changes which would aid in the remanufacturing process help a great deal in making remanufacturing cost-effective and efficient. Though there are many design guidelines scattered across literature, each study talks about making design easier for a specific step in the remanufacturing process like design for ease of access, disassembly or reassembly. There are no existing guidelines that specify design for repair or reconditioning process using additive manufacturing. This study focuses on compiling all the existing set of design guidelines for different phases/steps in remanufacturing and adding the design guidelines for remanufacturing using additive manufacturing to them. This study also elaborates the application of these guidelines with a case study.

1.2 Overview of Proposed Framework

The purpose of this study is to create a set of design guidelines for remanufacturing using additive manufacturing techniques. It involves extensive review of existing literature on design for remanufacturing and building on to it. These design guidelines are built into a tabular form, which helps designers in making choices under conflicting circumstances. Many times there are existing guidelines, but their application is unclear or too difficult to implement. To eliminate this confusion, the study also includes a case study demonstrating the application of the developed design rules. Overall, the below research objectives define the scope of this research:

1. Study existing literature of design for remanufacturing to identify and to develop design guidelines that facilitate remanufacturing using additive manufacturing.
2. Compile and consolidate these design guidelines, so that they can be understood and applied easily.
3. Explain the application of these rules through case studies.

The tool being used to compile and consolidate these design guidelines is a TRIZ matrix and the AM technique being used for the case study is direct energy deposition (DED). TRIZ matrix is a problem-solving tool, which consists of inventive solutions to contradicting parameters. It provides an easy path to choose between the numerous design guidelines based on the required situation. DED technique has been chosen for this study as it is the most convenient AM technique available for remanufacturing.

1.3 Thesis Roadmap

Though the concept of remanufacturing and additive manufacturing has been around for the last 30 years, it is only now that AM is being used or studied as a potential tool for remanufacturing. Hence, there is limited research so far on this topic and there are no guidelines or rules to make the use of AM for remanufacturing easier and more efficient. This study focuses on creating those guidelines or rules, to remanufacture components using additive manufacturing. Chapter 2 explains about remanufacturing, each process/step involved and the barriers to remanufacturing in detail. It also explains the various AM techniques that can be used for remanufacturing and the challenges of using AM for remanufacturing. This section also covers the existing literature on research done in this field so far.

Table 1-1: Thesis roadmap

Literature Review	Method: TRIZ Matrix	Application
Gather the existing design guidelines for remanufacturing 1. Introduction and steps in remanufacturing 2. Barriers to remanufacturing 3. AM techniques being used for remanufacturing 4. AM in remanufacturing 5. A complete search of databases for design for remanufacturing guidelines.	The tool used to present all the design guidelines in the form of a matrix 1. Introduction to TRIZ 2. Use and applications of TRIZ. 3. TRIZ for remanufacturing design guidelines	Explain the application of design guidelines using a case study 1. Method and materials used. 2. The procedure used to remanufacture 3. Analysis of results, followed by discussion.

Chapter 3 provides a detailed explanation of the proposed methodology with figures and examples. The tool used to build the design guidelines and their interpretation is described in detail. Chapter 4 contains a case study where an actual part is remanufactured using AM and focuses on how the design guidelines devised in chapter 3 have aided in the remanufacturing of a part.

Finally, the thesis concludes in chapter 5 where the results of section 3, backed up by the case study in section 4 are discussed and explained. The limitations and drawback of this thesis are addressed including scope for future work informed by this thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Remanufacturing

With globalization, manufacturing of parts has spread across the globe and has created a way to mass produce products at lower costs and accessible to a larger customer base. With cheaper availability of parts and frequent design updates from industries (especially electronics) waste generation has substantially increased. To combat the rising climate temperatures and waste produced, the concept of sustainability has been introduced in every field possible. With rapidly rising popularity for sustainability, manufacturers are also focusing on making their parts, products, and process sustainable. Reuse, repair and recycle are the most popular terms resonating with sustainability and green consumption. In this context, remanufacturing is another term gaining popularity swiftly. So, what is remanufacturing and how is it different from the other terms? To address this question, let us go over all the definitions including remanufacturing.

- Reuse: It is the process of using functional parts from retired assemblies (Amezquita et al., 1995).
- Repair: Repair is the process of fixing or mending damage or a faulty part so that it is functional, but this does not necessarily have a warranty or a clean look. (Amezquita et al., 1995)
- Refurbish / Recondition: The process of restoring a component to an acceptable condition and cleaning it so that it looks as close to a new one as possible and providing warranty

to it. Refurbished products are preferable over repaired ones generally. (Amezquita et al., 1995)

- Recycle: “A resource recovery method involving the collection and treatment of a waste product for use as a raw material in the manufacture of the same or a similar product” (GEMET 2000).
- Remanufacturing: The process of turning used products into products with quality and functionality similar to new products or better than new products. Remanufactured parts also have the warranty of a new product (Giuntini et al., 2003).

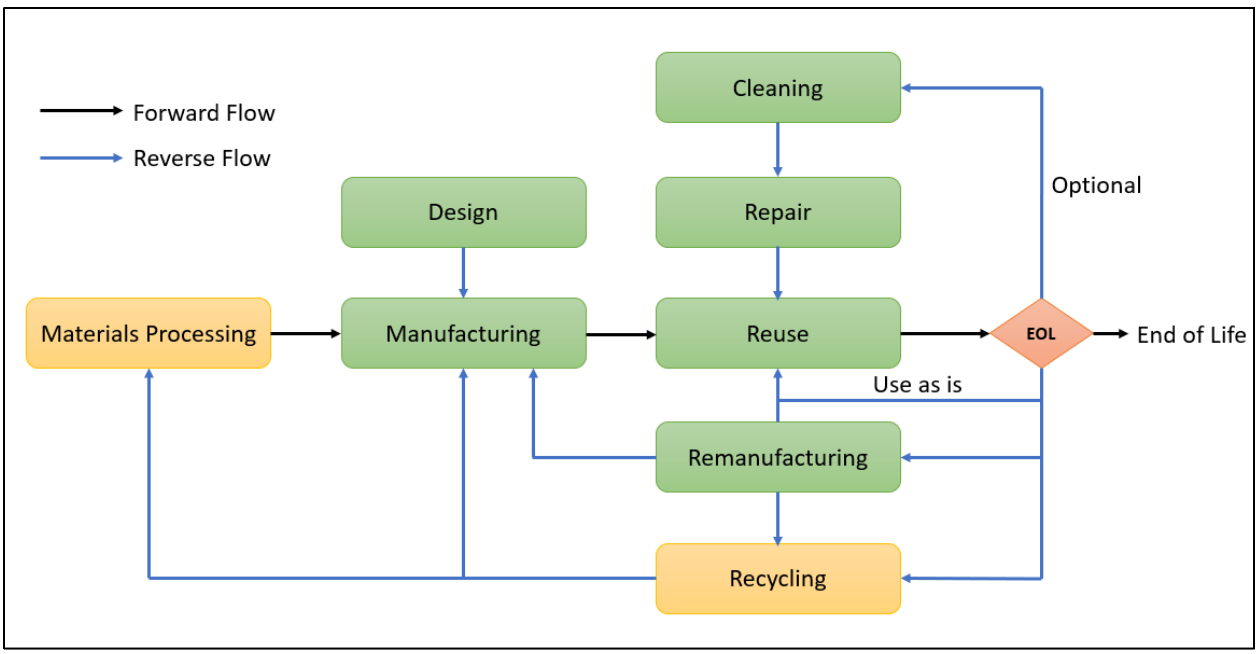


Fig 2-1. Remanufacturing as an alternative in the product life cycle (Ortegon et al., 2014)

Fig 2-1 illustrates the role of repair, reuse and remanufacturing in the life cycle of a product. Often remanufacturing is confused with repair/ refurbishment. Remanufacturing is not just repairing a product, or extending its life cycle a little more. It is bringing the part back to as good as new, or better than a new product functionally and aesthetically. Remanufacturing need not necessarily be done for damaged parts. Used goods that are still functional can also be remanufactured for improved properties. Table 2 provides the differences between remanufacturing and repair processes through different phases of the product life cycle (Gray et al., 2008).

Table 2-1: Difference between remanufacturing and repair of products (Gray et al., 2008)

Remanufacture	Repair
Applicability	
Used Products	Defective Products
Defective Products	-
Process	
Complete Disassembly	Failure Detection
Cleaning of all parts	Disassembly of some parts
Redemption of parts to as new state/ Replenishment of new parts/Upgrading of parts	Restoration or replacement of defective parts
Product Reassembly	Reassembly of parts
Characteristics	
Industrialized process	Mechanic's work
Overall restoration to like new condition	Individual repair of defect
Customer receives anonymous product	Customer keeps his/her own product
Like-new or lifetime warranty	Warranty covering repair work only
Upgrading to state-of-art technology	Product retains earlier standard

Of all the above-mentioned sustainable processes, remanufacturing might be the best approach, if it is feasible. This is because a remanufactured part is as good as a new one in terms of quality and comes at a lower price. From an environmental perspective, it also reduces a lot of waste and at the same time provides new products, thus reducing the number of components needed to manufacture as well. Compared to recycling, remanufacturing is more preferable as it adds value to damaged parts by bringing them back to like new condition, instead of scrapping the material and rebuilding it from the scratch (Ijomah et al., 2007). Existing studies show that remanufacturing saves up to 90% of materials compared with new product manufacturing (Steinhilper et al., 1998) and that the energy required for original production versus remanufacturing can reach ratios of six to one (Nasr et al., 2010). Overall, remanufacturing has environmental as well as economic benefits, which is a terrific combination in the present world.

Though remanufacturing has numerous benefits, it still is in its initial stages and there are many unexplored aspects to it that need to be researched. Not all parts or products can be remanufactured. For example, small parts such as screws, nuts, bottles, etc. might be more economical if they are new products rather than remanufactured. There are no set of rules as to what can and cannot be remanufactured. However, remanufacturing works best when parts/components are of high value, complex to manufacture a new one and not outdated with newer designs easily. Components such as engine parts (Acharya et al., 2015), gas and steam turbine blades (Wilson et al., 2014), steel molds (Payne et al., 2016), dies (Leunda et al., 2011), aircraft components, office photocopiers (Kerr et al., 2001), excavation equipment, power bearings, defense equipment, computer and television equipment (Hatcher et al., 2013), etc. are usually remanufactured. Remanufacturing of computer and telecommunication equipment poses a unique challenge because the models of computers or phones become obsolete in a very short span of time given the constant updates in models and designs.

On the surface, remanufacturing might seem to be a simple process as it does not actually involve manufacturing any new component or does not start from scratch. However, remanufacturing is a complex process and involves several steps. The following section explains the steps involved in remanufacturing in detail.

2.2 Remanufacturing Process

Remanufacturing primarily involves a used part coming to the remanufacturing facility. These used parts are then disassembled, cleaned and inspected (Matsumoto et al., 2016). Sometimes, if inspection of the part can be done before disassembly, it is done so. If any of the components are not functioning, they are repaired. If not, these non-functional parts are replaced with new ones. These functional old parts and the replaced new ones are reassembled together and the whole assembly is tested again. This gives us the remanufactured parts. Fig 2-2 outlines all the steps involved in remanufacturing.

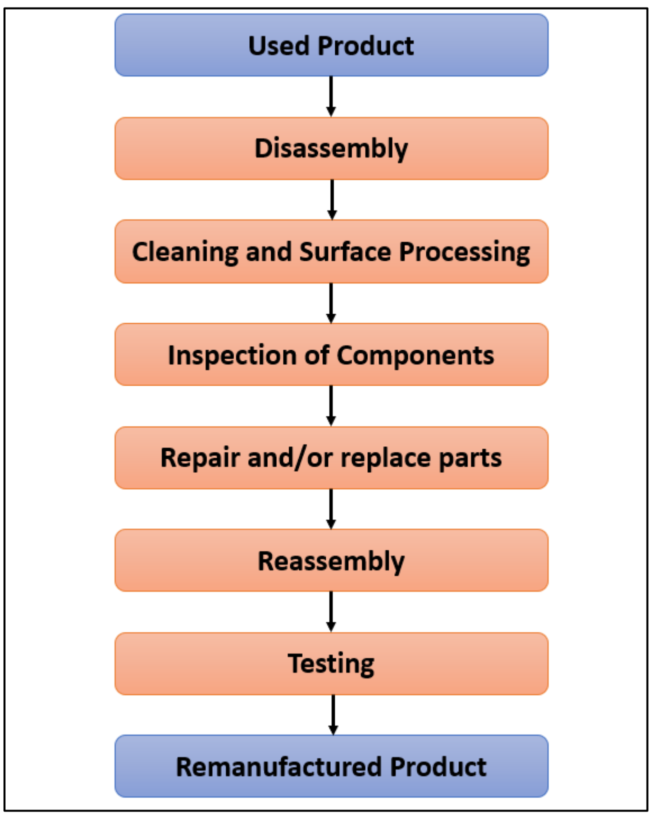


Fig 2-2. Steps involved in the remanufacturing process (Matsumoto et al., 2016)

2.2.1 Disassembly

Once a used product arrives at a remanufacturing facility, the useful core needs to be cleaned and refurbished. Disassembly typically involves taking apart individual parts of a component. The major challenges of disassembling a part are the complicated design of the product and the means to handle it. If the design is not facilitating disassembly, it takes a lot of time and skill to disassemble a part without damaging it. The process only gets more complicated and costly with an increase in the size and complexity of the product.

2.2.2 Cleaning

Cleaning in remanufacturing is an industrial process for the reduction of the number of contaminants present in or on a component until the specified cleanliness level has been reached in the remanufacturing process (Liu et al., 2013). Cleaning for remanufacturing is more challenging and different than regular cleaning for maintenance or repair. Cleaning helps identify any defects or surface damage during the inspection phase. It is also used to remove any contaminants and facilitate repair and reassembly. Additionally, remanufactured parts should be as good as new or better than a new part. From that perspective, the product needs to be aesthetically clean too. Fig 2-3 shows how often cleaning needs to be done during a remanufacturing process.

Cleaning is often the most pollution causing process in remanufacturing (Liu et al., 2014). It is one of the most demanding steps and is a particularly essential process in remanufacturing because the quality of used product (referred to as cores – Wei et al., 2015) surface cleanliness directly determines the part's surface analysis and the following process such as surface inspection, reconditioning, reassembly and painting processing (Liu et a., 2013). Cleaning is one of the costliest processes in automobile parts remanufacturing and in photocopier remanufacturing (Hammond et al., 1998; Chang et al., 2013).

Major contaminants in the cleaning phase are usually oil and grease and a combination of detergents, alcohols, and degreasers are used for this purpose. However, these substances are volatile organic compounds and add to environmental pollution. The disposal of these liquids after cleaning is also environmentally harmful. As a result, other environment-friendly substances such as supercritical CO2 are increasingly being used for this purpose (Liu et al., 2013, 2014, 2015; Li et al., 2015).

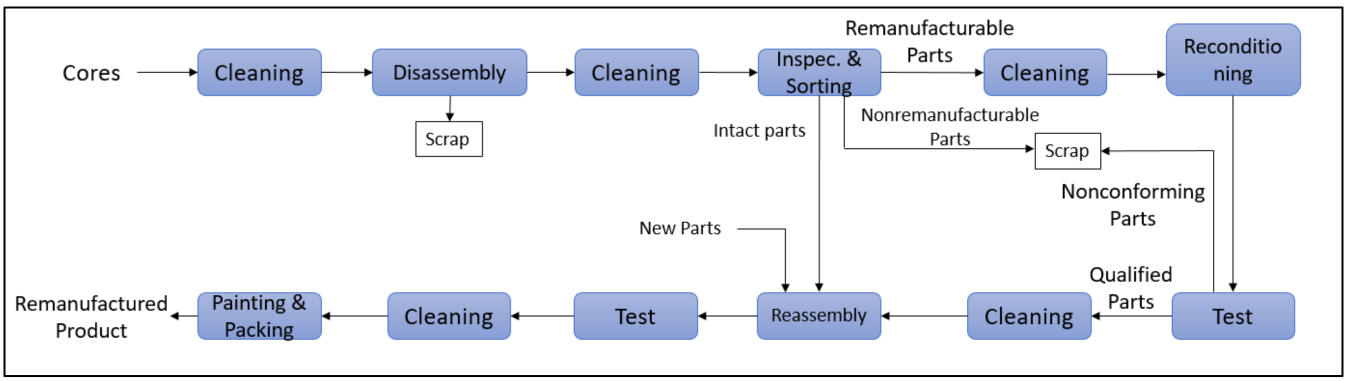


Fig 2-3. Common technological process of remanufacturing (Liu et al., 2014)

2.2.3 Inspection

Inspection is the process of identifying any defects in a part or component. The factor that made inspection most difficult is the knowledge of the employee carrying out the work (Hammond et al., 1998). Unlike the manufacturing of new components, where inspection is carried out using sampling techniques, remanufacturing requires 100% inspection (Brent et al., 2004). This is done to increase the second user's confidence in remanufactured products, and it is thought to explain why remanufactured products appear to have better reliability than new products (Brent et al., 2004). Inspection is typically done on the core of the component and on disassembled parts.

Depending upon the skill of the person inspecting, if unrepairable defects can be identified before disassembly or cleaning itself, the part can be discarded without further ado. However, it is difficult to identify that and often inspection is done after disassembly and cleaning.

The inspection includes visual inspection and in the later stages, measurement and/or dimensional inspection, to determine the wear of the part. The product is first visually inspected, followed by physical, identification and performance inspections (Errington et al., 2013). Fig 2-4 depicts the inspection process for a product which needs to be remanufactured.

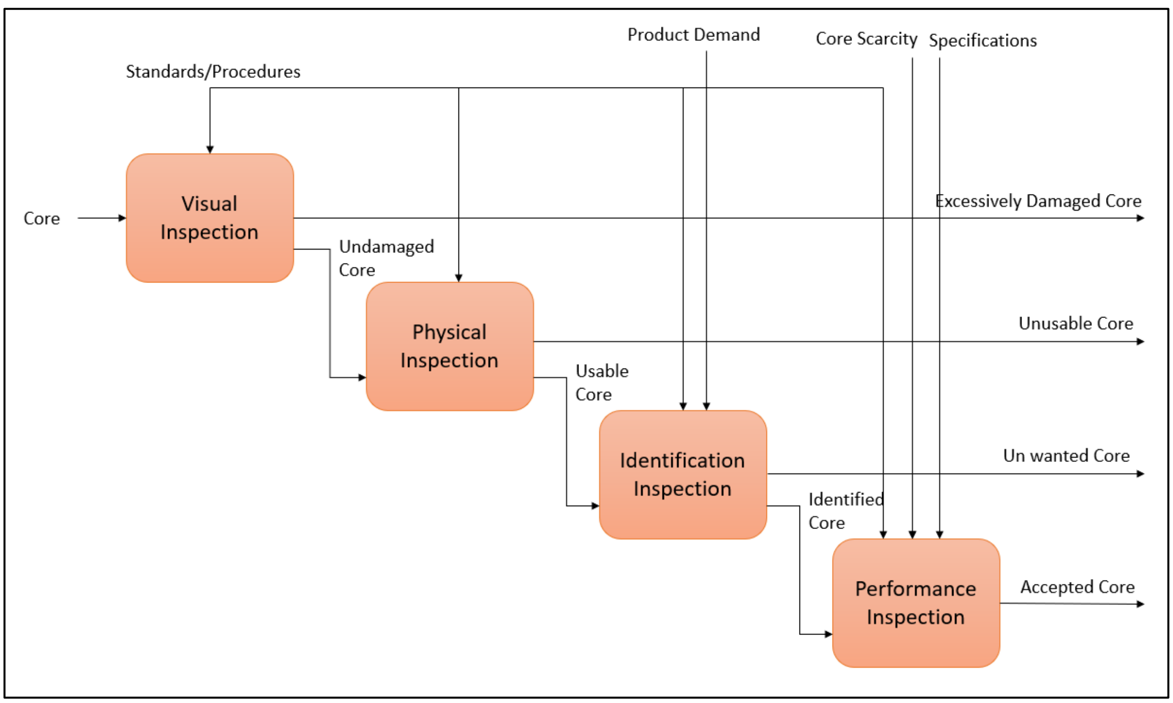


Fig 2-4. Inspection Process/procedure of a core (Errington et al., 2013)

2.2.4 Repair and Refurbishment

This phase in remanufacturing typically involves repair of damaged, corroded and worn out parts. If the parts are beyond repair, they are replaced. Repair of these cores is done using different means and techniques depending upon the type of damage. If the part is worn out, the surface is cleaned, and additional material is deposited through welding, which is later machined off to get the desired dimensional tolerances. Laser repair technologies are also being extensively used for repair process (Liu et al., 2011, Chen et al., 2014).

A part should be made free of rust, corrosion, wear and any other surface irregularities. Laser-aided repair techniques are the most widely used for this purpose (Wang et al., 2002)]. Methods such as oxy-acetylene flame spray welding and electrical arc spraying have been used to repair abrasive damages to loader pins (Wang et al., 2012). In the last couple of decades, with advancements in metal additive manufacturing techniques, repair of worn out parts has become possible. Techniques such as SLM, EBM, DED, and LENS are being researched extensively and used to some extent in the remanufacturing industry. Hybrid manufacturing techniques, which involve both additive as well as subtractive methods at the same time are also being researched as a potential application.

If the parts cannot be repaired, or if replacement of the part is easier than repair, the damaged parts are scraped off and replaced with new ones. Fig 2-5 shows the role of repair, recycle and remanufacturing in a closed loop process.

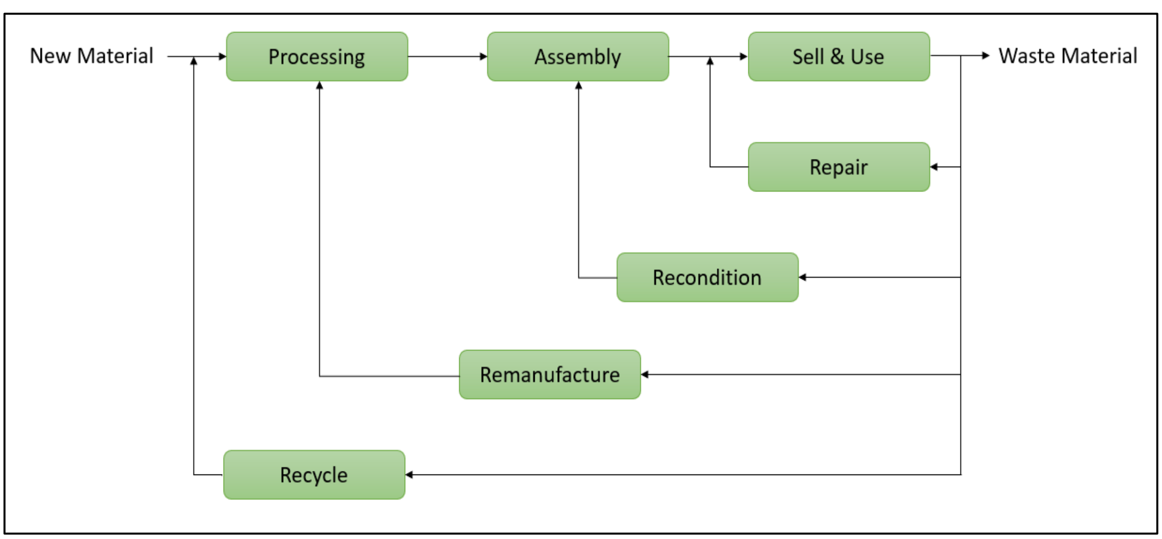


Fig 2-5. Repair, recycle and remanufacture through closed-loop process (Wang et al., 2002)

2.2.5 Reassembly

After the core is disassembled, cleaned, inspected and repaired/replaced, the next step in the process is to reassemble all the parts back. Assembling the parts depends on the size of the parts, which determines the sequence of assembling parts. For reassembly, all the required parts need to be available at the time of assembling and hence inventory also plays an important role. It is important to determine the parts to be stored and the sequence of assembling parts.

2.2.6 Testing

Unlike newly manufactured parts, remanufacturing needs a higher degree of testing (almost 100%). Non-destructive testing methods are most preferred for this part because we need to identify defects without actually damaging the part as a higher percentage of parts need to be tested. Of late, NDT techniques such as Metal Magnet Memory testing (MMM) are gaining rapid popularity, due to their ability to identify even fine cracks and defects without destroying the parts (Zhang et al., 2011).

2.3 Barriers to Remanufacturing

Though remanufacturing is being hailed by environmentalists and nature lovers, there are many factors that hinder it from becoming widespread. This section is going to address the issues or barriers to remanufacturing.

In a competitive market, it is not every day that a consumer hears about remanufactured parts or goods. Given that remanufacturing is synonymous with reusing parts in layman's terms, it is often mistaken as reconditioned or refurbished parts, thus not being the first option for many customers. Everyone would want to buy a new product, over a remanufactured one as they simply are not aware that it is as good as a new one or might even be better than a new one. This lack of awareness is a major drawback for many remanufacturers or even OEM companies too, as the market is limited to those consumers who are aware of it (Matsumoto et al., 2016). Added to that, the demand for remanufactured parts is comparatively very low and the lead times are quite unpredictable as one cannot know when they might get a scrapped part/core. Cleaning, inspection, disassembly, repair, and reassembly of the part are often time-consuming and demand skilled labor (Ijomah et al., 2007). As a result, the price of the part is comparatively higher than repaired or refurbished ones, thereby decreasing the already meager demand even further.

There are two types of remanufacturers - Independent remanufacturers (IRs) and OEM remanufacturers (Matsumoto et al., 2016). OEM remanufacturers have an advantage over IRs as they have the design of the product, spare parts required for any replacement, equipment to remanufacture and trust of customers (Lund et al., 1983). However, OEMs might be reluctant to remanufacture. This is because, remanufactured products are not only much cheaper and better than their new products but also compete with their new products. However, remanufactured parts do not give the sales margins/profits that the new products give (Linton et al., 2008; Atasu et al., 2008). Sometimes, OEMs might even design the products to be difficult or extremely expensive to remanufacture, so that IRs cannot remanufacture their products (Seitz et al., 2007; Matsumoto et al., 2011).

Additionally, factors such as technology advancement and availability of effective remanufacturing tools are also major barriers to remanufacturing (Ijomah et al., 2007). Especially in case of the electronics industry, the volume of phones, laptops or any other electronic gadgets produced and sold is huge. But these products are replaced very fast with changing models and specifications. Hence, the same model phone or laptop becomes obsolete and old, thus making remanufacture of such products useless. There are also no tools specifically designed to use for remanufacturing and are usually designed based on experience (Ijomah et al., 2007).

Last but not least is the availability of technology required to repair damaged cores. Until recently, the primary mode of repair was through welding. But welding can only be used for two-dimensional repairs and might not always give the desired results. Due to the excessive heat during welding, the grain structure might change and as a result, the strength of the part might be different. However, one solution to repair 3D damage to cores is through metal additive manufacturing. In the following section, the AM techniques that can be used for remanufacturing are discussed.

2.4 Additive Manufacturing

Additive manufacturing, also known as 3D printing or rapid prototyping, is the process of adding material layer by layer to form a part using a 3D model data. Unlike conventional manufacturing processes such as CNC machining which remove nearly 95% of material from the raw material to create the product, AM can print functional parts without any extra tooling, producing very minimal waste (Murr et al., 2012). This manufacturing technique is extensively used for making plastic prototypes and models for testing. However, in the last couple of decades, with huge advancements in AM, it is being potentially researched and used for remanufacturing of expensive parts. Not all AM techniques can be used for remanufacturing. Many techniques such as Fused Deposition Modeling (FDM), Stereolithography (SLA), and Continuous Liquid Interface Production (CLIP), etc. are used for making plastic parts only and cannot be applicable for repairing metal parts. Metal AM techniques such as Electron beam Melting (EBM), Selective Laser Melting (SLM), Direct Energy Deposition (DED), Laser Engineered Net Shaping (LENS), etc. are used for remanufacturing. Metal AM techniques can be broadly categorized into 1. Powder bed systems such as SLM (Xu et al., 2015) and EBM (Murr et al., 2012a) and 2. Powder feed systems such as DED (Heigel et al., 2015) and LENS (Frazier et al., 2014, Mudge et al., 2007). In the following sections, these techniques are explained in detail.

2.4.1 Selective Laser Melting

SLM is an AM technique which consists of melting metal selectively to form parts of the desired shape. It is a powder bed fusion (PBF) AM technique, consisting of a machine setup, laser system, metallic powder bed, and a galvanometric mirror. A galvanometric mirror is an electromechanical instrument that senses when an electric current is passed through it and deflects the light beam focused on to it accordingly (Britannica.com 2019). SLM typically involves a Computer-aided Design (CAD) model of the part, sliced into thin layers using a slicing software. A laser beam is used to create each layer of the sliced CAD model on the powder bed. The powder bed consists of a substrate onto which each layer of metal powder is put and melted in the desired shape by the laser beam. This laser beam, in turn, is controlled by a galvanometric mirror. Fig 2-6 shows the fabrication of parts through SLM.

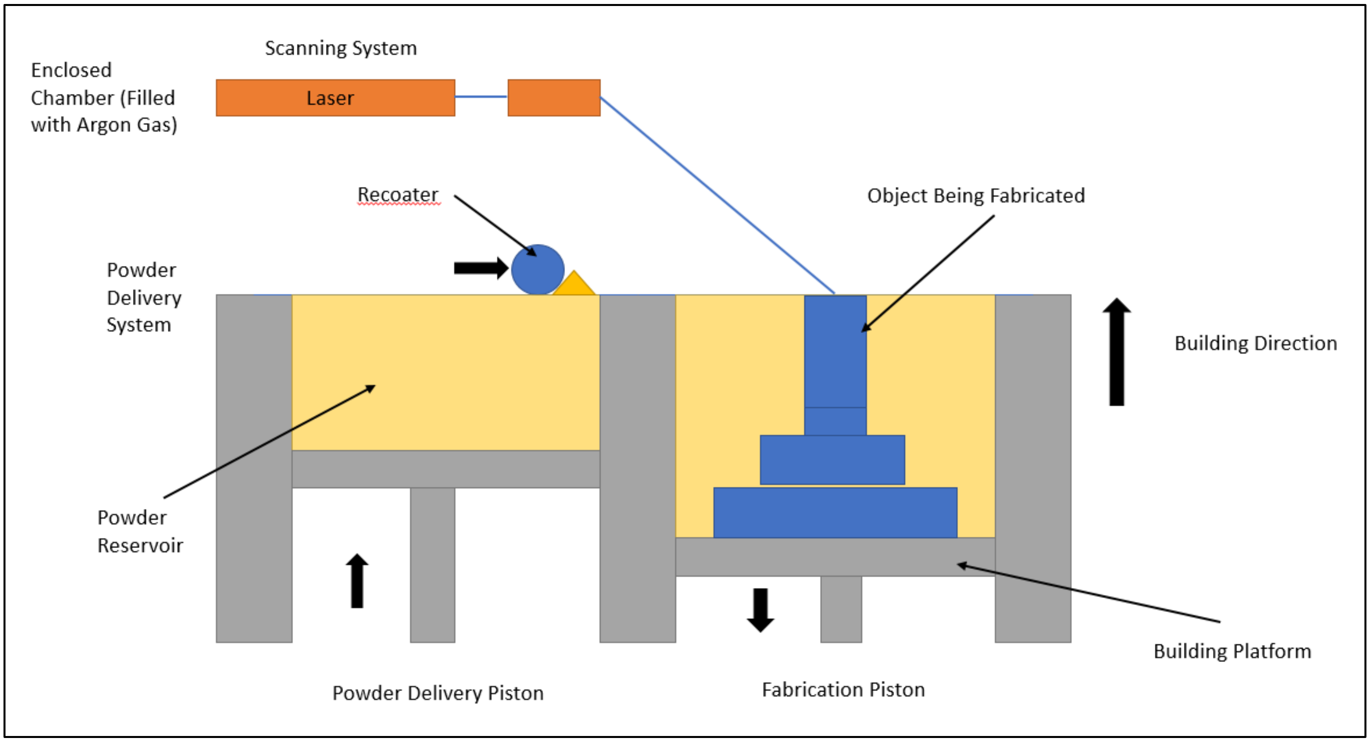


Fig 2-6. Selective laser melting process (Jiao et al., 2018)

A layer of metal powder is put on to the substrate using a roller or a re-coater. The laser beam 'selectively' melts the powder in the required shape. This laser beam is projected with the help of a galvanometric mirror. After the first layer is melted, the substrate/bed is lowered to accommodate the next layer of powder. The laser beam then selectively melts the next layer, at the same time fusing it with the first one. The process is repeated until the part is completely built. The built part is removed from the powder bed and further processed as required by the application. The whole process is done in an inert atmosphere in order to prevent oxidation and other forms of contamination from reactive gases.

The major drawback of SLM is that it has all the issues that arise with a melt pool such as residual stresses, distortions, pore formation, etc. Distortions also arise due to the temperature gradient between the first layer and the subsequent layers. To reduce this gradient, the whole chamber is usually heated to a certain temperature.

Additionally, the formation of pores/voids between different layers (Thijs et al., 2010) and within the layer (Attar et al., 2014) pose a challenge to fabricate parts using SLM. It was observed that the pore formation was caused due to lower laser power, which could not melt all the powder particles (Attar et al., 2014). However, increasing the laser power might lead to over melting and evaporation, which in turn might lead to the creation of gas pores (Clijsters et al., 2014). It was observed that process parameters such as scanning speed and layer thickness played a major role in decreasing porosity and increasing density of SLM parts (Badrossamay et al., 2009).

While fabricating a part using AM techniques, surface quality has been a major concern and SLM is not an exception to that. The surface quality of SLM parts has been investigated by many researchers (Alrbaey et al., 2014; Strano et al., 2013; Kruth et al., 2005). There are a few solutions to provide better surface finish but most of them are an additional surface finish process which require the part to be removed from the build plate.

2.4.2 Electron Beam Melting (EBM)

EBM is another type of PBF AM technique. It is similar to SLM, but an electron beam is used to heat the metal powders instead of a laser beam. EBM consists of an electron gun to generate a cloud of electrons, which are directed on to the metal powders using magnetic fields. The electron beam is generated by heating up the tungsten filament in the electron gun.

Magnetic coils are used to control the diameter and direction of the electron beam generated. Fig 2-7 shows a schematic diagram of the EBM process.

EBM is done in near vacuum to avoid collision of electrons with any gas molecules (Gong et al., 2013). This vacuum condition also provides an environment where components with reactive metals can be easily fabricated. In this process, a metal rake is used to lay the layers of powder instead of rollers / re-coaters used in SLM. The powder surrounding to the part is sintered with electron beams so that the build platform remains stable with each new layer being put on it. To remove the part from this sintered mass of powder, it is passed through a powder recovery system. Because of this pre-heating/sintering of the powder bed, EBM requires fewer support structures compared to SLM. However, the electron beam cannot be as focused as a laser beam. Hence, SLM can produce parts with better accuracy than EBM. EBM can use multiple electron beams and thus can have faster build rates than SLM (Gong et al., 2013). Some of the major differences between the processes are listed in table 2-2 below.

Table 2-2: Difference between EBM and SLM. Adopted from Gibson et al. (2009) as referenced in Gong et al. (2013)

CHARACTERISTIC	EBM	SLM
Thermal Source	Electron	Laser
Atmosphere	Vacuum	Inert gas
Scanning	Deflection Coils	Galvanometers
Energy Absorption	Conductivity – Limited	Absorptivity – limited
Powder Preheating	Uses Electron Beam	Uses infrared heaters
Scan speed	Very Fast, Magnetically driven	Limited by galvanometer inertia and motor sizing
Energy cost	Moderate	High
Surface Finish	Moderate-poor	Excellent to moderate
Feature Resolution	Metals	Excellent
Materials	Metals - Conductors	Polymers, metals and ceramics

Similar to SLM, EBM also has similar challenges of pore formation within the layers and between the layers (Gaytan et al., 2009; Murr et al., 2009). These defects could be minimized by using optimum process parameters - scanning speed, layer thickness and energy density.

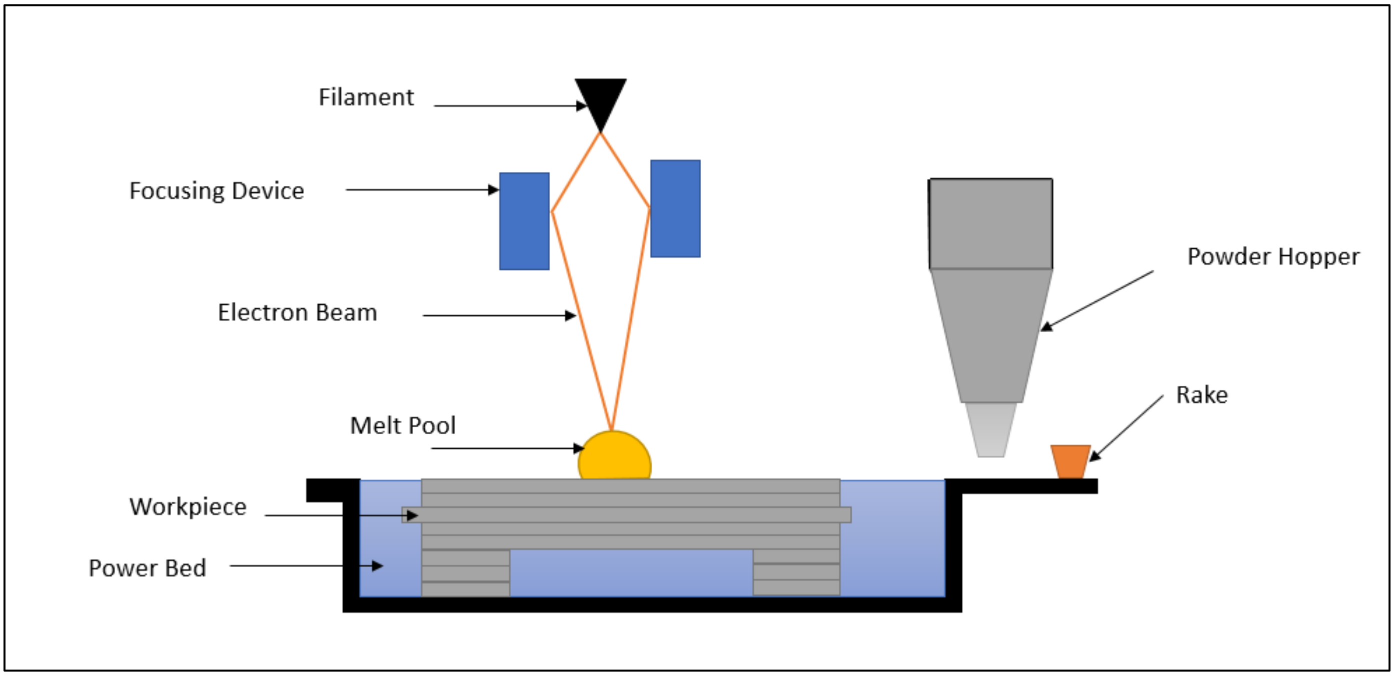


Fig 2-7. Schematic of EBM process (Walton et al., 2017)

2.4.3 Direct Energy Deposition (DED)

DED is a type of powder feed system (PFS), which uses a focused laser or an electron beam. Unlike a powder bed system which consists of a powder bed where the laser is focused to make a part, powder feed system consists of a powder being fed into the laser/electron beam, where it melts and gets deposited on the substrate.

2.4.3.1. Direct laser deposition/direct metal deposition (DLD/DMD)

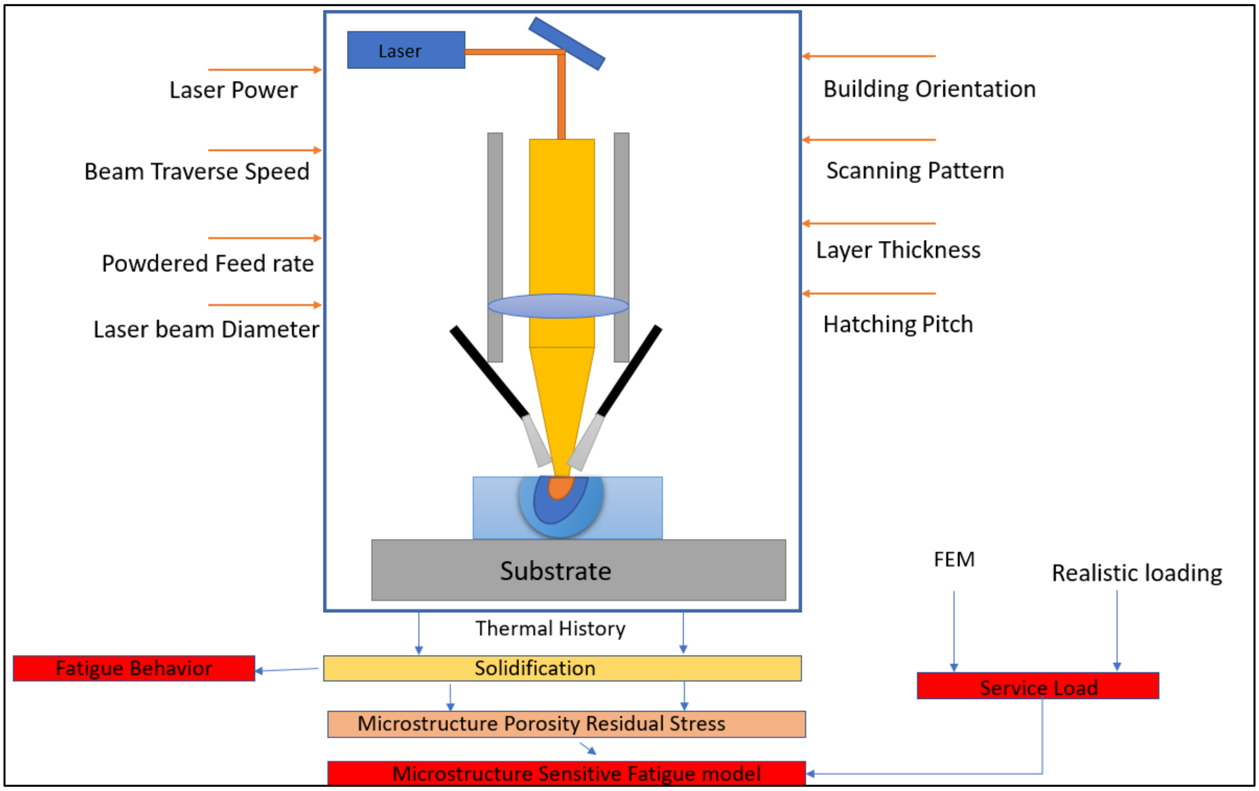


Fig 2-8. Schematic of the DLD process (Shamsaei et al., 2015)

As shown in Fig 2-8, DLD consists of a laser beam, which is focused on the substrate using a lens and the powder is fed through the nozzles surrounding it. This is typically known as a "deposition head" (Gibson et al., 2015) including laser system, powder nozzles and any inert gas tubing that might be present. This whole process is carried out in an inert gas atmosphere to reduce oxidation of the part. Because of the presence of a deposition head, the head can be moved to deposit material, when the substrate is too heavy or huge to be moved (Gibson et al., 2015).

Process parameters such as traverse speed of the laser, laser power, powder feed velocity, laser beam diameter, etc. play a major role in controlling the quality and build time of the part

(Thompson et al., 2015). If the process parameters are not controlled properly, voids/cavities may occur due to lack of bonding between layers (Thompson et al., 2015; Gibson et al., 2015).

2.4.3.2. Laser engineered net shaping (LENS)

LENS is the most commercialized form of DLD. Unlike DLD, which usually had a single nozzle for powder feed, LENS consists of multiples nozzles for powder feed (Thompson et al., 2015). The use of an inert atmosphere and laser type allows for many types of metals to be fabricated using LENS. With the help of multiple nozzles and focused laser beam, LENS can deposit more amount of material a lot faster than other laser additive processes. However, due to the thickness of depositing material, it is difficult to produce parts with greater precision. Only near net shape of the parts can be fabricated, hence the process is named as Net Shaping. Additionally, support structures are not utilized during this process making it unfavorable for tall structures. Fig 2-9 provides a pictorial representation of the LENS process.

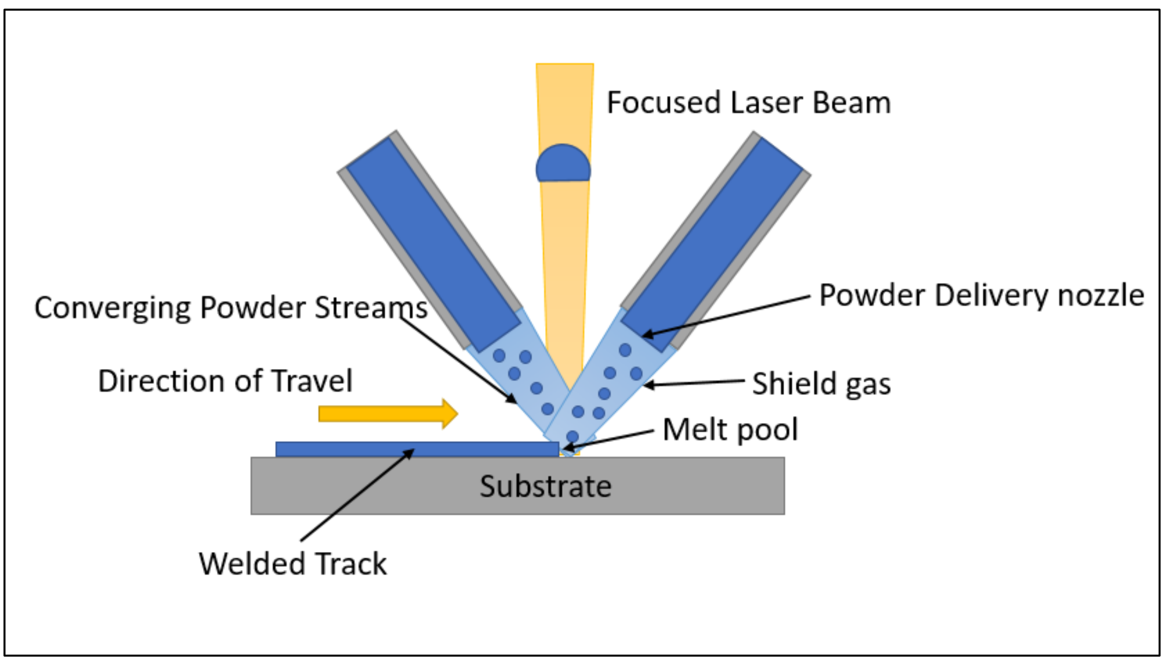


Fig 2-9. Schematic of LENS process [Bintoa.com 2019]

2.4.5. Cold Gas Dynamic Spray (CDGS)

The cold gas dynamic spray is a type of additive technology which involves spraying of metallic powders at supersonic speeds, thereby fusing them together. Pressurized gas is preheated and passed through a De-Laval nozzle, which increases the velocity of the gas particles to supersonic speeds. These high-speed gas particles are focused on to a substrate or the part which needs to be cold sprayed. Due to the high heat and velocity of the particles, plastic deformation of particle and substrate occurs, forming a solid-state mechanical bond. Thus, this process does not require any melting of the metal to add material. Hence it is called the cold spray process. Fig 2-10 is a schematic diagram of the CDGS process.

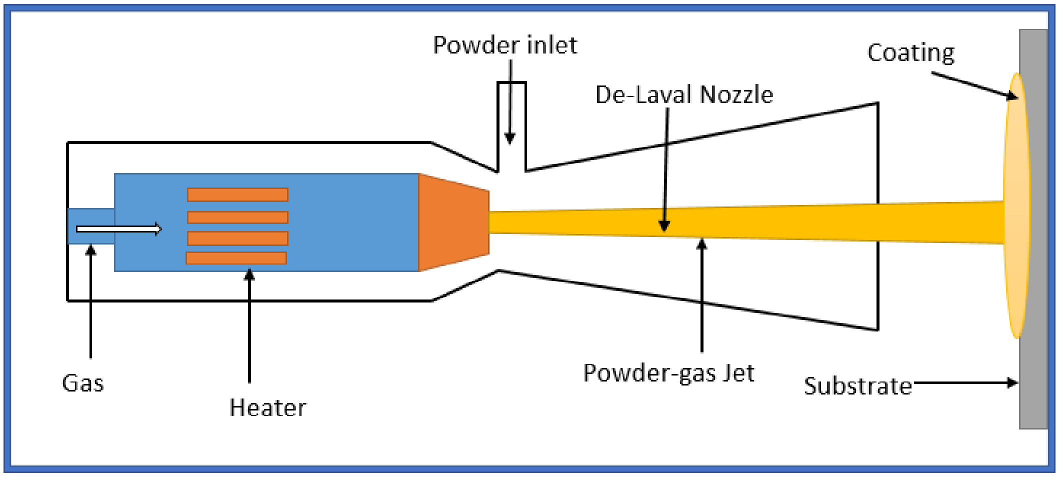


Fig 2-10. Schematic of CGDS [tessonics.com 2019]

This process has been usually used for coating purposes but is now being explored for additive manufacturing as well (Raoelison et al., 2017). The strength of cold sprayed parts can be optimized by controlling the process parameters such as particle shape and size, particle velocity, the temperature of the pressurized gas, etc. (Hussain et al., 2013).

Though cold spraying has many advantages such as no powder melting, no grain growth or phase changes, no oxidation, high density, and low porosity, etc., there are a few limitations to it. Cold sprayed parts have near zero ductility and consume large quantities of heated gas compared to thermal spray processes. There are also only a limited number of materials that can be sprayed, and the substrate must be hard enough to hold the high-velocity particles (Villafuerte et al., 2015). Added to that, it is a line of sight process (Davis et al., 2004). Complex structures or interior diameters are difficult to be sprayed using this method.

2.5. Additive Manufacturing in Remanufacturing

As discussed in the earlier sections, remanufacturing has different stages/steps, namely, disassembly, cleaning and surface processing, inspection of components, repair or replace parts, reassembly, and testing. The above discussed AM techniques can be used in the repair/refurbishing stage of the process. For example, the DED process allows for the feeding of a different mix of materials through multiple nozzles, creating improved functionality of parts. This way, remanufactured parts can have improved properties (Matsumoto et al., 2016). Wilson et al. (2014) have used the laser direct deposition method (LDD is also known as direct laser deposition - DLD) to remanufacture a damaged turbine blade. In order to reconstruct a damaged part, the geometry of the damaged or worn out region needs to be replicated into a 3D model. Zhang et al. (2015) have focused on creating geometric models of different types of damaged regions through a hybrid B-rep model. Paulic et al. (2014) used the concept of reverse engineering along with optical scanning to obtain the digital image of the desired structure. With the help of 3D scanning technology, a point cloud of the object is developed, which in turn is used to create a CAD model of the existing part. This CAD model has been used to print the volume buttons used in the audio setup of cars through SLM technology (Paulic et al., 2014). SIEMENS has also used the SLM process to remanufacture gas turbine burner tips (Navrotsky et al., 2014). Mudge et al. (2007) have used the LENS process to repair gas turbine compressor seal, Ti bearing housing and atomizer drive coupler gear. Lee et al. (2007) used cold spray process to repair a damaged Al mold. After spraying the mold has been milled to get the required surface finish and dimensions. Champagne et al. (2008) also used cold spray process to repair Magnesium rotorcraft components. Payne et al. (2016) used laser metal deposition (LMD/DLD) process to repair artificially worn out H13 (an alloy of chromium, molybdenum, and vanadium with steel) steel molds and compared it to the traditional welding repair technologies. Buican et al. (2014) have used SLM process to remanufacture stainless steel gears (316L) of a sewing machine and documented the whole procedure of scanning, repairing, improving and remanufacturing the part.

In all the above-mentioned processes, the properties of the part such as microstructure, hardness, tensile and compressive strength, fatigue strength, etc. have been studied for a different combination of process parameters in each process. Lourenço et al. (2016) observed the fracture and fatigue behavior of aerospace components fabricated through LMD using AerMet 100 alloy powder. The results showed that LMD has contributed to an increase in fatigue life. Pinkerton et al. (2008) studied the challenges of repairing internal defects with the LMD process. It has been suggested that a groove or slot to the depth of the defect needs to be machined, in order to be repaired using the LMD process. Table 4 is a summary of remanufactured components using additive manufacturing techniques.

Table 2-3. Components remanufactured using AM techniques

S.No	AM Process	Remanufactured part	Material used	Paper
1	LENS	Gas turbine compressor seal	Inconel 718	Mudge et al., 2007
2	LENS	Bearing housing	Ti-6Al-4V	
3	LENS	Atomizer drive coupler gear	420 Stainless Steel	
4	CDGS	Al Mould	Al	Lee et al., 2007
5	CDGS	Magnesium rotor craft components	5056 Al (composition Al–5Mg–0.1Mn–0.1Cr	Champagne et al., 2008
6	LMD	H13 steel molds	H13 Steel	Payne et al., 2016
7	SLM	Gear from sewing maching	Stainless Steel 316L_30	Buican et al., 2014
8	LDD	Turbine Blades	316L	Wilson et al., 2014
9	SLM	Car volume button	Polyamide PA2200	Paulic et al., 2014
10	SLM	gas burner tips	-	Navrotsky et al., 2014
11	SLE (Scanning laser Epitaxy)	Turbine engine hot section component	IN 100	Acharya et al., 2015
12	LAAM	Turbine blade knife edge	IN 100	Bi et al., 2011
13	Laser Cladding/ LDD	Die repair	CPM 10V, Vanadis 4	Leunda et al., 2011
14	LDD	Rail Tracks	Co-Cr Stellite 6 alloy	Clare et al., 2013

As can be observed from the above table, the DED process is the most popular AM technique for repair and remanufacturing of parts. DED is more famous compared to PBF manufacturing because, DED technique has a movable nozzle head, which can aid in creating desired geometry along with an arbitrary trajectory (Ahn et al., 2011; Ruan et al., 2006). Even though traditional techniques such as welding are used for some repair processes, DED has many advantages over those. Wilson et al. (2014) discussed that GTAW is not compatible with a number of advanced material and their high operating temperatures and does not result in adequate component design. Table 5 lists some of the differences between conventional welding processes and Laser Metal deposition (LMD also known as DED).

Table 2-4. Difference between LMD and conventional welding process (Mahamood et al., 2017)

LMD Process	Conventional Welding Process
Superior metallurgical bonding	Less superior metallurgical bonding
Low heat input	High heat input
Low dilution is possible	High dilution rate
Low heat affected zone	High heat affected zone
Process cannot be controlled manually	Manual process control possible
Higher thermal diffusivity and conductivity	Lower thermal conductivity and diffusivity
High equipment cost	Low equipment cost
Surface quality can be controlled	Surface quality cannot be controlled
Good for repair or remanufacturing of 3D part or equipment	May not be applicable for certain parts due to heat damage it will cause to the parts
Can be used to produce 3D part from the scratch	Cannot be used to build a 3D part

2.6. Design for Remanufacturing

Many times, it is hard to remanufacture a part because it is very costly or time-consuming to perform one of the steps involved in remanufacturing. These issues can be eliminated by designing a product so that it is convenient to remanufacture it at its End of Life (EOL). But the problem is that designers are not used to keeping EOL of a part in mind when designing a component and there are only a limited set of guidelines on how to design for remanufacturing. Designing for the ease of any of the steps involved in remanufacturing such as disassembly, sorting, cleaning, refurbishment, reassembly, and testing, is considered as designing for remanufacturing (Shu et al., 1999). It can be as simple as giving more access to parts for cleaning or using a smaller number of parts to make disassembly and assembly easier. However, it is important to keep in mind the whole remanufacturing process and that its primary purpose is to reuse a product. If a part cannot be reused after refurbishment or disassembly, then there is no point in focusing on designing for cleaning or testing (Shu and flowers 1998). There are numerous research papers that focus on remanufacturing for different requirements and the design guidelines that will be required for specific products. Of all, Sundin et al**.,** (2005) have best summarized the relationship between product properties and remanufacturing steps into a remanufacturing property (Rempro) Matrix as shown in Fig 2-11.

Product Property \ Remanufacturing Step	Inspection	Cleaning	Disassembly	Storage	Repair	Reassembly	Testing
Ease of Identification	x		x	x			x
Ease of Verification	x						
Ease of Access	x	x	x		x		x
Ease of Handling			x	x	x	x	
Ease of Separation			x		x		
Ease of Securing						x	
Ease of Alignment						x	
Ease of Stacking				x			
Wear Resistance		x	x		x	x	

Fig 2-11. Rempro Matrix (Sundin et al., 2005)

Other studies focus on the design guidelines for individual steps in a remanufacturing process.

These design guidelines have been discussed in detail in the following sections.

2.6.1. Design for Disassembly (DFD)

Disassembly of a part can sometimes be quite time taking and tricky to perform, without damaging the part. In order to design for disassembly, steps as simple as reducing the number of fasteners or joints should be kept in mind. Hatcher et al. (2013) observed that almost all disassembly for remanufacturing is manual. Having permanent joints such as welding, or brazing should also not be used if the part is to be remanufactured (Sundin et al., 2005). Soh et al. (2014) encapsulates that design for disassembly generally constitutes of 3 aspects - (i) the adoption of suitable methodologies, (ii) implementation of technologies and (iii) incorporation of human factors (ergonomics), for an efficient disassembly process. Table 6 provides design rules for disassembly gathered from the literature**.**

Table 2-5. Guidelines for DFD (Bogue et al., 2007)

Factors affecting Disassembly	Design Guidelines
Product Structure	Minimize the component count
	Minimize product variants
Materials	Minimize the use of different materials
	Use recyclable materials
	Eliminate toxic or hazardous materials
Fasteners, joints and connections	Minimize the number of joints and connections
	Eliminate hidden joints
	Mark non-obvious joints
	Use fasteners rather than adhesives
Characteristics of components for disassembly	Good accessibility
	Low weight
	Robust, minimize fragile parts
	Non hazardous
Disassembly Conditions	Design for automated disassembly
	Eliminate the need for specialized disassembly procedures

2.6.2. Design for Cleaning

It has been observed that cleaning is usually the most labor-intensive step in the whole remanufacturing process (Gonzalez et al., 1983). The most important factor in cleaning is the ease of accessibility. The easier it is to access the surface to be cleaned, the faster it can be cleaned. A designer should keep in mind not just the accessibility of the surface, but also the type of cleaning material used. The cleaning material used should also not be stuck in the grooves or surface. Solvent-based fluids used for cleaning are not always environment-friendly and prolonged exposure to those fumes is unhealthy for workers as well (Shu et al., 1999). It has been suggested that sharp corners and grooves often are hard to clean and might be unhygienic in food storage areas (Sundin et al., 2005). Fig 2-12 and 2-13 provide simple design changes that increase accessibility for cleaning. These changes can also be put as design rules for cleaning.

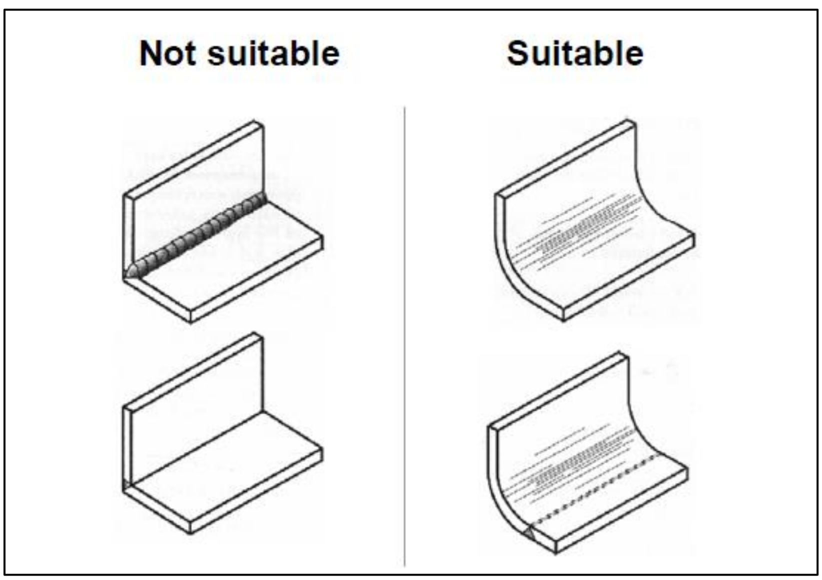


Fig 2-12. Design of corners for cleaning accessibility (Sundin et al., 2005)

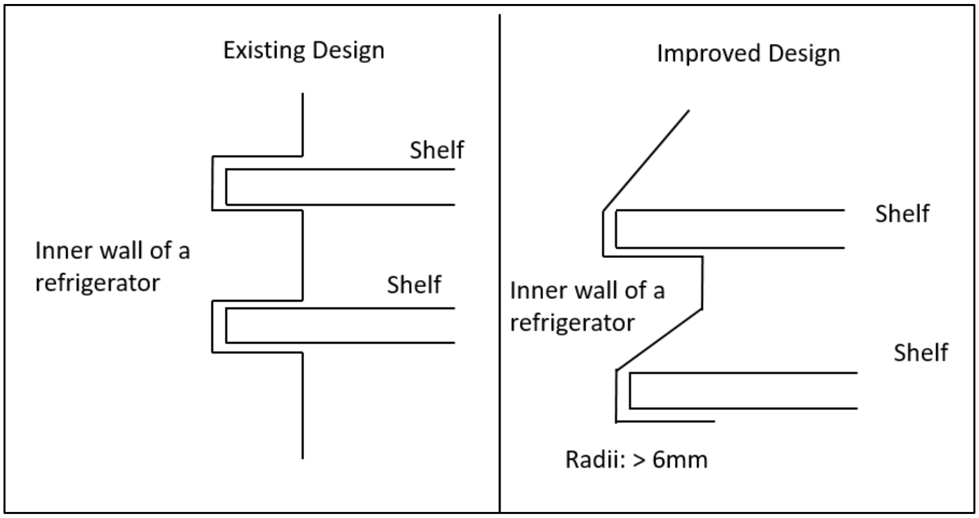


Fig 2-13. Design recommendations for easier access to clean a refrigerator (Sundin et al., 2005)

2.6.3. Design for Inspection and Testing

Inspection can be done either before or after disassembly. If a part is too complex and dirty, it cannot be inspected and hence inspection will be done after disassembly and cleaning for such parts. Inspection greatly depends on the ease of accessibility, identification, and verification (Sundin et al., 2008). Testing is usually followed by the reassembly of the part. Sundin et al., (2008) deduced that testing also depends on the ease of access and identification. Like disassembly, both testing and inspection are non-value-added processes and the time required for them should be minimized as much possible.

2.6.4. Design for Repair or Replacement

As discussed in the previous sections, repair of worn out parts can be performed by welding, but it might not always be successful. If not, these parts must be replaced. It is important that the replaceable parts are available on time for the remanufactured part to be delivered in a timely manner. In recent years additive manufacturing is also being used as a potential remanufacturing technique. Ease of access, handling, separation and wear resistance are the desired product properties for repairing the product (Sundin et al., 2008). For example, a part being repaired by AM techniques should fit into the bed of the AM machine. If the part is too big or too complex to handle, it will be difficult to repair it using any techniques available. If the assembly is a big one, the part can be split into sub-assemblies and the smaller assembly or part can be fixed. Hence, it is important that the product is easy to disassemble as well.

2.6.5 Design for Reassembly (DFR)

The design guidelines for reassembly are similar to those of disassembly. Below table lists some of the common design guidelines for assembly.

Table 2-6. DFA guidelines (Bras et al., 2014)

Design For Assembly Guidelines
1. Overall component count should be minimized
2. Minimize the use of fasteners
3. Maximize component accessibility
4. Design components for symmetry about their axes of insertion
5. Avoid component characteristics that complicate retrieval (tangling, nesting and flexibility)
6. Design components for end to end symmetry
7. Make use of chamfers, leads and compliance to facilitate insertion.
8. Avoid creating too many disconnected subassemblies to be joined later

However, some DFD guidelines might have a negative effect on the assembling process. For example, using two-way snap fits or breakpoints, using water-soluble adhesives, using weak joining materials, etc. are all good for DFD but not for DFA (Bras et al., 2014).

2.7. Summary on Research Gaps

Overall, this chapter introduces the concept of remanufacturing and elaborates the processes and stages involved in it. The methods to remanufacture are discussed with additive manufacturing techniques being the latest technology. Different types of AM techniques which can be used for remanufacturing are discussed in detail. Section 2.5 provides literature on where and how these AM techniques have been used to remanufacture products. The importance of design for remanufacturing is explained in section 2.6. Designing for various steps in the remanufacturing process are discussed in the following sections.

In conclusion, the existing literature review covers some of the design guidelines required for specific steps in remanufacturing, but there is no existing literature on the design guidelines required for a part to be remanufactured using additive manufacturing. This study focuses on building onto the existing guidelines and developing new guidelines to remanufacture using additive manufacturing techniques.

CHAPTER 3

METHODOLOGY

3.1. Introduction

This section explains about the methodology used to develop the design guidelines for remanufacturing and its application. As mentioned in Chapter 1, the method used is TRIZ matrix, which is known as the theory of inventive principles matrix. Section 3.2 elaborates about the design guidelines collected from the literature so far, both additive manufacturing and remanufacturing alike. Section 3.3 explains what a TRIZ matrix is, how to use it and its applications in various fields of study. Section 3.4 provides great detail on how the design guidelines have been developed using TRIZ and how to use them as well.

3.2. Existing Design Guidelines

So far, the available design guidelines for remanufacturing have been discussed. The literature also holds numerous design guidelines for additive manufacturing of parts. However, the real challenge arises when one has to use these guidelines cascaded throughout the literature. It is often very tedious and inefficient to go through so many research papers for a simple design rule. In order to make it efficient to find a design rule, this study is focused on developing a tool that can be easily accessed and used.

This section provides a comprehensive review of all the existing design guidelines for remanufacturing and additive manufacturing alike, that have been gathered from the literature. Fig 3-1 summarizes the design guidelines for remanufacturing while Fig 3-2a and Fig 3-2b provides a list of additive manufacturing design rules, which are relevant for remanufacturing.

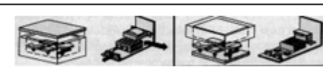
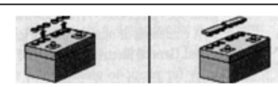
PRINCIPLE	EXPLANATION	SOURCE
Homogeneity	Use same tools for assembly and disassembly. This way, special tools for each process will be eliminated, saving time and cost Use same type of materials, which are resistant to cleaning materials	Kelly and Dowie Rules (engineering.purdue.edu)
Reduce Sharp Corners	Sharp corners are not easily accessible to clean. Hence it is better to have curved or chamfered corners, so that cleaning will be easier.	Sundin et al., 2005
Single Direction	Use one disassembly direction to avoid reorientation. Disassembling from multiple directions requires reorientation, which is again time consuming	Kelly and Dowie Rules (engineering.purdue.edu)
Avoid close spaced horizontal projections	Cleaning in between horizontal spaces is not easy. It is hard to access such areas, making cleaning difficult. Having some inclination on one surface (as shown in fig.) will make cleaning much easier and less time consuming.	Sundin et al., 2005
Avoid long disassembly paths		Kelly and Dowie Rules (engineering.purdue.edu)
Pre-Design for easy access		Kelly and Dowie Rules (engineering.purdue.edu)
Hollow structures	Low Weight, minimizing fragile parts, non hazardous	Bogue et al., 2007
Reduce the number of operations performed		Kelly and Dowie Rules (engineering.purdue.edu)
Avoid permanent joints	Having permanent joints like rivets, welds etc. is very time consuming to remove Mark non-obvious joints	Ijomah et al, 2007 Bogue et al., 2007
Wear resistance	Having smooth surfaces will accumulate lesser dust and are easier to clean. The material or surface of the part should be wear resistant in order to survive the cleaning fludis.	Amezquita et al., 1995
Smooth surface	Having smooth surfaces will accumulate lesser dust and are easier to clean	Amezquita et al., 1995
Mark/Eliminate hidden joints	Reducing hidden joints will reduce the time for disassembly. If hidden joints are a necessity, mark the locations of hidden joints.	Bogue et al., 2007
Mark testing points	Testing points should be marked and accessible. This will facilitate easier and quicker verification process	Sundin et al., 2005

Fig 3-1. Design guidelines for remanufacturing compiled from the literature

Even though all the necessary guidelines have been provided, there are still many rules. It is hard to keep so many guidelines in mind while designing a part. To address this issue, a TRIZ matrix will be developed in the following sections. The next section explains what a TRIZ matrix is, how to use it and its applications.

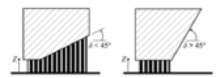
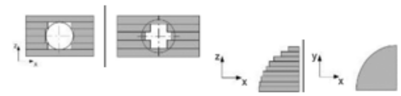
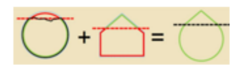
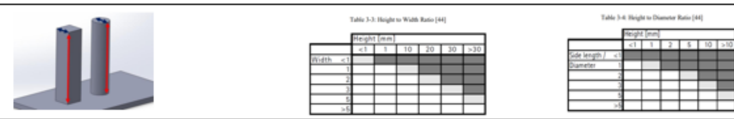
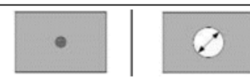
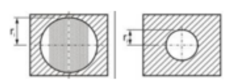
PRINCIPLE	EXPLANATION	SOURCE
Perforate with holes	If the reason for the open structure is simply weight reduction, it may be easier to perforate it with holes (ideally less than 6mm in dia) that will reduce weight, but not require any supports. Massive objects may cause major deformations due to heat accumulation Reduce the amount of volume where not absolutely necessary 	Gerard and Sahner, 2017 Crucibledesign.co.uk
Avoid overhangs that might need supports	Use of angular, concave or convex shapes instead. However, this will work for small radii only. 	Samperi M. T., 2014
Proper orientation	Reduction of support structures through right choice of orientation 	Schnabel et al., 2017
Reduce Stair Case efect	Avoid staircase effect by adequate part orientation. (Z represents building orientation) Consider allowance in part design for horizontally aligned bores due to staircase effect. 	Kranz et al., 2015
Design optimisation for better quality	Correct shape reduces the support structures required and sometimes even the surface finish required. 	Reinarz et al., 2014
Desired Height to width ratio		Samperi M.T., 2014
Part size must consider substrate plate dimensions	Rotate, scale and separate parts if necessary 	Kranz et al., 2015
Minimum diameter	Bores below minimum diameter show powder adhesion 	Kranz et al., 2015
Maximum Diameter	Bores' insides that regularly require support structures can be manufactured without support structures if the bores' inner radii are small enough 	Adam et al., 2015

Fig 3-2a. Additive manufacturing design guidelines which are relevant for remanufacturing

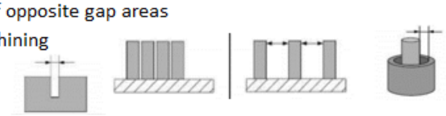
PRINCIPLE	EXPLANATION	SOURCE
Gaps between round features, vertical orientation and manfactured parts	Gaps below specifications may show large powder adhesion and merging of opposite gap areas Consider free space between manufactured parts in order to ease final machining 	Kranz et al., 2015
Reduce Gap areas	Design gap areas as small as possible Reduction of powder adhesion 	Kranz et al., 2015
Use cavities	Use cavities in order to reduce the part volume to be exposured. Also, the wt of part will be reduced Reduction of manufacturing time and cost. 	Kranz et al., 2015
Multiple openings fo complex parts	They can be espace holes or equally spaced openings for easy powder removal. 	Kranz et al., 2015
Remove material	Avoid material accumulation Reduction of part volume reduces manufacturing time, cost and wt of the part 	Kranz et al., 2015
Offset supports	The most simple form of support is to fill in the area that needs support, and then cut this out when the build is complete by wire cutting or machining. If the support area is to be removed with wire cutting, a small hole needs to be placed in the support area to allow the wire to be located  Offset supports require less machining. They rise vertically and then angle in to support specific surfaces. The base of the support is usually removed with the wire cut removal of the part, requiring only the supported surface to be machined.	Crucibledesign.co.uk
Avoid sharp corners	Design parts with minimum radii of approximately 0.5mm. Very sharp edges cannot be built in DMLS 	Crucibledesign.co.uk

Fig 3-2b. Additive manufacturing design guidelines which are relevant for remanufacturing

3.3. TRIZ Matrix

TRIZ is a Russian problem-solving tool, an acronym for the Russian phrase 'teorija rezhenija izobretatelskih zadach' which means "Theory of Inventive Problem Solving" (Rantanen et al., 2007). It has been developed by Genrich Altshuller (a Russian scientist, 1926–1998), and team, to streamline scientific innovations and patents being made (Ilevbare et al., 2013). It was observed by Genrich Altshuller that many of the patents had the same ideas, but did not know of the other's existence. He also observed that the solution to a particular problem could also be applied as a solution to some other problem from a very different genre.

3.3.1. Introduction to TRIZ

Altshuller believed that most inventions solved a contradiction. He argued that a problem or challenge could not be solved without deteriorating some other feature. For example, if a car needs to have a stronger outer body, the thickness of material can be increased, but this will also increase the weight of the object. Thus, improving the strength is increasing the weight of the object as well. One solution to this problem is to use composite materials, which are lighter and stronger. Altshuller was able to predict this through his TRIZ matrix nearly 50 years ago when composite materials did not exist (Jack Hipple, 2019).

According to the concept of TRIZ, most of the problems faced in the world already might have solutions elsewhere. It is just that nobody is aware of the solutions outside their field. The concept of TRIZ is based on finding those general solutions, to one's specific problems. Fig 3-3 provides a representation of this approach (mazur.net).

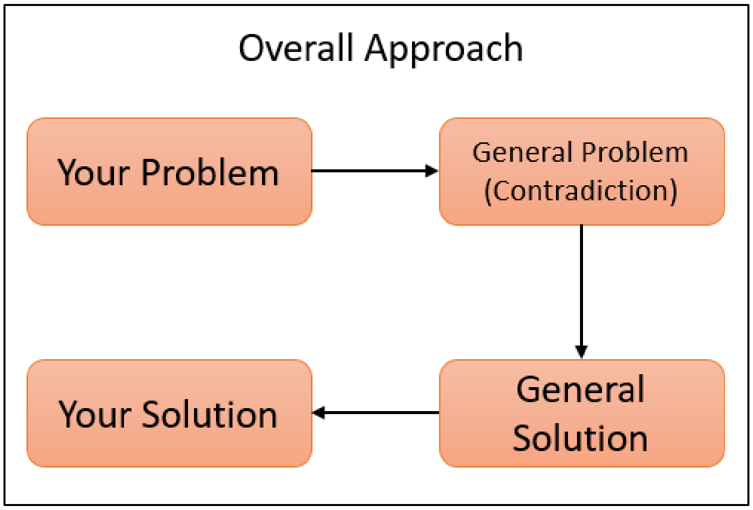


Fig 3-3. TRIZ approach to problem-solving (mazur.net)

This problem-solving approach of TRIZ is used to eliminate contradictions. There are two kinds of contradictions – technical contradictions and physical contradictions (Barry et al., 2010).

1. Technical Contradictions are those contradictions with trade-offs. For example, increasing the strength of the car is good, but this increases the weight of the car, which is bad.
2. Physical contradictions are those where the system has opposite requirements like the coffee served to customers should be hot, but should be cold at the same time for safe drinking (Barry et al., 2010).

After analyzing more than 3 million patents (Barry et al., 2010), Altshuller and team deduced that there are 39 problems or contradictions which generally arise in any challenging situation. Table 3-1 lists these contradictions. TRIZ matrix consists of the improving features (contradictions) in the first column of the matrix and worsening features or those features that need to be preserved in the first row of the matrix. The same contradictions are present in the row and the column. Fig 3-4 shows a typical TRIZ matrix.

Table 3-1: Contradictions in a TRIZ matrix (Triz40.com)

SNo.	Contradictions
1	Weight of moving object
2	Weight of stationary object
3	Length of moving object
4	Length of stationary object
5	Area of moving object
6	Area of stationary object
7	Volume of moving object
8	Volume of stationary object
9	Speed
10	Force (Intensity)
11	Stress or pressure
12	Shape
13	Stability of the object's composition
14	Strength
15	Duration of action of moving object
16	Duration of action by stationary object
17	Temperature
18	Illumination intensity
19	Use of energy by moving object
20	Use of energy by stationary object
21	Power
22	Loss of energy
23	Loss of substance
24	Loss of information
25	Loss of time
26	Quantity of substance/ the matter
27	Reliability
28	Measurement accuracy
29	Manufacturing precision
30	Object-affected harmful factors
31	Object-generated harmful factors
32	Ease of manufacture
33	Ease of operation
34	Ease of repair
35	Adaptability or versatility
36	Device complexity
37	Difficulty of detecting and measuring
38	Extent of automation
39	Productivity

Depending upon the problems/contradictions, 40 general solutions have been provided by Altshuller. Table 3-2 lists the 40 inventive principles.

Worsening Feature → / Improving Feature ↓		1 Weight of moving object	2 Weight of stationary object	3 Length of moving object	4 Length of stationary object	5 Area of moving object	6 Area of stationary object	7 Volume of moving object	8 Volume of stationary object	9 Speed	10 Force (intensity)	11 Stress or pressure	12 Shape	13 Stability of the object' compositio	14 St	15 D
1	Weight of moving object	+		15, 8, 29,34		29, 17, 38, 34		29, 2, 40, 28		2, 8, 15, 38	8, 10, 18, 37	10, 36, 37, 40	10, 14, 35, 40	1, 35, 19, 39	28, 27, 18, 40	5, 34, 31, 35
2	Weight of stationary object		+		10, 1, 29, 35		35, 30, 13, 2		5, 35, 14, 2		8, 10, 19, 35	13, 29, 10, 18	13, 10, 29, 14	26, 39, 1, 40	28, 2, 10, 27	
3	Length of moving object	8, 15, 29, 34		+		15, 17, 4		7, 17, 4, 35		13, 4, 8	17, 10, 4	1, 8, 35	1, 8, 10, 29	1, 8, 15, 34	8, 35, 29, 34	19
4	Length of stationary object		35, 28, 40, 29		+		17, 7, 10, 40		35, 8, 2,14		28, 10	1, 14, 35	13, 14, 15, 7	39, 37, 35	15, 14, 28, 26	
5	Area of moving object	2, 17, 29, 4		14, 15, 18, 4		+		7, 14, 17, 4		29, 30, 4, 34	19, 30, 35, 2	10, 15, 36, 28	5, 34, 29, 4	11, 2, 13, 39	3, 15, 40, 14	6, 3
6	Area of stationary object		30, 2, 14, 18		26, 7, 9, 39		+				1, 18, 35, 36	10, 15, 36, 37		2, 38	40	
7	Volume of moving object	2, 26, 29, 40		1, 7, 4, 35		1, 7, 4, 17		+		29, 4, 38, 34	15, 35, 36, 37	6, 35, 36, 37	1, 15, 29, 4	28, 10, 1, 39	9, 14, 15, 7	6, 35, 4
8	Volume of stationary object		35, 10, 19, 14	19, 14	35, 8, 2, 14				+		2, 18, 37	24, 35	7, 2, 35	34, 28, 35, 40	9, 14, 17, 15	
9	Speed	2, 28, 13, 38		13, 14, 8		29, 30, 34		7, 29, 34		+	13, 28, 15, 19	6, 18, 38, 40	35, 15, 18, 34	28, 33, 1, 18	8, 3, 26, 14	3, 19, 35, 5
10	Force (Intensity)	8, 1, 37, 18	18, 13, 1, 28	17, 19, 9, 36	28, 10	19, 10, 15	1, 18, 36, 37	15, 9, 12, 37	2, 36, 18, 37	13, 28, 15, 12	+	18, 21, 11	10, 35, 40, 34	35, 10, 21	35, 10, 14, 27	19, 2
11	Stress or pressure	10, 36, 37, 40	13, 29, 10, 18	35, 10, 36	35, 1, 14, 16	10, 15, 36, 28	10, 15, 36, 37	6, 35, 10	35, 24	6, 35, 36	36, 35, 21	+	35, 4, 15, 10	35, 33, 2, 40	9, 18, 3, 40	19, 3, 27
12	Shape	8, 10, 29, 40	15, 10, 26, 3	29, 34, 5, 4	13, 14, 10, 7	5, 34, 4, 10		14, 4, 15, 22	7, 2, 35	35, 15, 34, 18	35, 10, 37, 40	34, 15, 10, 14	+	33, 1, 18, 4	30, 14, 10, 40	14, 26, 9, 25
13	Stability of the object's composition	21, 35, 2, 39	26, 39, 1, 40	13, 15, 1, 28	37	2, 11, 13	39	28, 10, 19, 39	34, 28, 35, 40	33, 15, 28, 18	10, 35, 21, 16	2, 35, 40	22, 1, 18, 4	+	17, 9, 15	13, 27, 10, 35
14	Strength	1, 8, 40, 15	40, 26, 27, 1	1, 15, 8, 35	15, 14, 28, 26	3, 34, 40, 29	9, 40, 28	10, 15, 14, 7	9, 14, 17, 15	8, 13, 26, 14	10, 18, 3, 14	10, 3, 18, 40	10, 30, 35, 40	13, 17, 35	+	27, 3, 26
15	Duration of action of moving object	19, 5, 34, 31		2, 19, 9		3, 17, 19		10, 2, 19, 30		3, 35, 5	19, 2, 16	19, 3, 27	14, 26, 28, 25	13, 3, 35	27, 3, 10	+

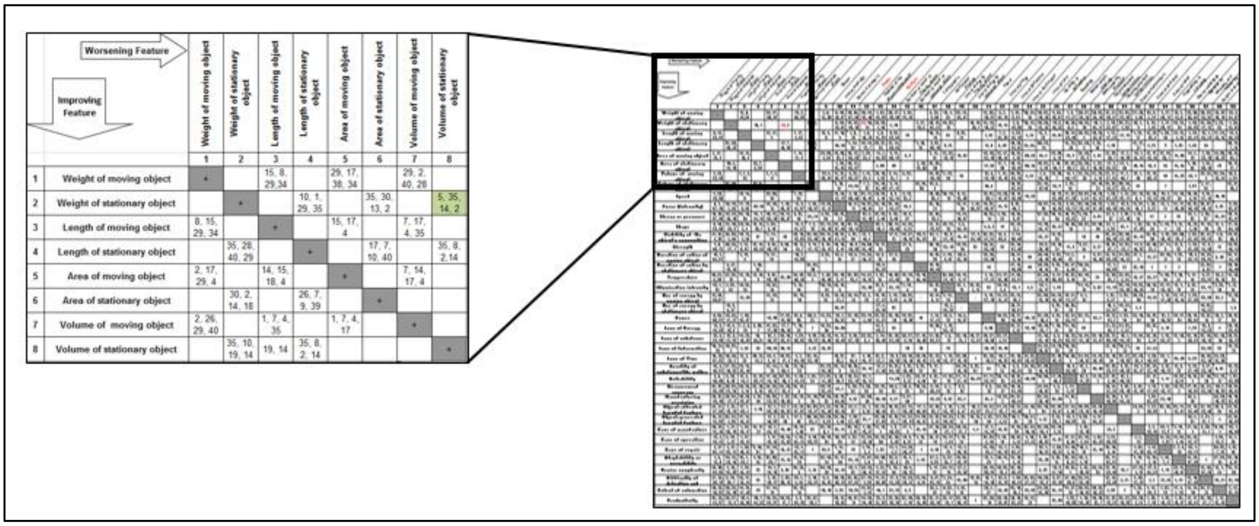
Fig 3-4. TRIZ Matrix showing improving and worsening features (Jack Hipple, 2019)

Table 3-2: 40 principles/solutions of TRIZ (Triz40.com)

Sno	Principles
1	Segmentation
2	Separating or taking out
3	Local quality
4	Asymmetry
5	Merging
6	Universality
7	Nested Doll
8	Anti weight/ Levitation
9	Preliminary anti-action
10	Preliminary action
11	Beforehand Cushioning
12	Equipotentiality
13	The other way round
14	Curvature
15	Dynamics
16	Partial or excessive actions
17	Another Dimension
18	Mechanical Vibration
19	Periodic Action
20	Continuity of useful action
21	Skipping
22	"Blessing in disguise"
23	Feedback
24	Intermediary
25	Self-service
26	Copying
27	Cheap short living objects
28	Mechanics substitution
29	Pneumatics & hydraulics
30	Flexible shells and thin films
31	Porous materials
32	Color changes
33	Homogeneity
34	Discarding and recovering
35	Parameter changes
36	Phase transitions
37	Thermal expansion
38	Strong oxidants
39	Inert atmosphere
40	Composite materials

3.3.2. Understanding TRIZ

This section talks about how to use the TRIZ matrix. As shown in Fig 3-4, a TRIZ matrix has improving and worsening features in its first column and row respectively. In Fig 3-5,



	Worsening Feature / Improving Feature	Weight of moving object	Weight of stationary object	Length of moving object	Length of stationary object	Area of moving object	Area of stationary object	Volume of moving object	Volume of stationary object
		1	2	3	4	5	6	7	8
1	Weight of moving object	+		15, 8, 29,34		29, 17, 38, 34		29, 2, 40, 28	
2	Weight of stationary object		+		10, 1, 29, 35		35, 30, 13, 2		5, 35, 14, 2
3	Length of moving object	8, 15, 29, 34		+		15, 17, 4		7, 17, 4, 35	
4	Length of stationary object		35, 28, 40, 29		+		17, 7, 10, 40		35, 8, 2,14
5	Area of moving object	2, 17, 29, 4		14, 15, 18, 4		+		7, 14, 17, 4	
6	Area of stationary object		30, 2, 14, 18		26, 7, 9, 39		+		
7	Volume of moving object	2, 26, 29, 40		1, 7, 4, 35		1, 7, 4, 17		+	
8	Volume of stationary object		35, 10, 19, 14	19, 14	35, 8, 2, 14				+

Fig 3-5. Expanded view of TRIZ

an expanded view of the TRIZ is shown. The numbers provided in the cells inside the matrix are the solutions from the list of 40 principles, presented according to the corresponding improving and worsening features. For example, consider the cell highlighted in green in the expanded view in Fig 3-5. The corresponding improving feature for that particular cell is “weight of stationary object” and the corresponding worsening feature is “volume of the stationary object.” The contradiction is read as, changing (increasing or decreasing) the weight of the object, while preserving the volume of the object. For this contradiction, the solutions presented are 2, 5, 14 and 35 from the list of principles. That is, to increase the weight of the object while preserving the volume the suggested solutions are 2-separating or taking out the parts, 5-merging them, 14-curvatures and 35-changing parameters. The numbers provided in the matrix are the numbers corresponding to the solutions presented in table 3-2. Thus, TRIZ provides multiple solutions for varied contradictions. The blank cells imply that all the principles can be applied to the particular contradiction (i-sim.org).

3.3.3. Applications of TRIZ

The previous section talks about how to read a TRIZ matrix to find corresponding solutions to problems/contradictions. This section provides practical examples of where TRIZ matrix can be applied and used. Consider the problem of noisy air conditioners. The air conditioner should be able to cool the whole interior space, but this requires a strong compressor, which makes more noise. Here, the contradicting features from the contradiction matrix are 31 - object-generated harmful factors (which is noise) and 36 – device complexity (the whole noise making conditioner). Here the worsening feature is the noise (object generated harmful factors) and the feature that needs to be improved or changed is the device complexity. The solutions provided for this contradiction are 1- segmentation and 19 – periodic action. From these solutions, it can be seen that the segmentation principle is a better fit to solve the problem. The solution could be to separate the compressor from the main air conditioner and keep it outside, thus reducing the noise (Elmansy, 2016).

The applications of TRIZ are not limited to technical fields alone. It can be applied to any problem in any field. For example, a furniture store in a small building wants to display its furniture (which needs to be large) but at the same time needs to be small to store inventory (so that it occupies as little space as possible). This is an example of a physical contradiction, where the requirements of the situation itself are opposites. From the 40 inventive principles, principle 1, segmentation, is the most viable one. The owners of the store can assemble the furniture for display and store the disassembled parts in flat packs, which will occupy less space for storage (mindtools.com).

TRIZ has also been applied to solve many research problems as well. It is being studied and applied in business and research fields alike. Srinivasan et al. (2006) used TRIZ to design safer chemical processes. Low et al. (2000) explored the applications of TRIZ in the field of eco-design and innovation. Wang et al. (2010) used TRIZ methodology in combination with lean six sigma approach to improving the efficiency of banking services. Zlotin et al. (2001) studied the applications of TRIZ in non-technical areas such as medicine and biology, safety and social and business fields. Shirwaiker and Okudan (2008) investigated the use of TRIZ manufacturing cases and proposed a synergistic use of TRIZ with Axiomatix Design. Shirwaiker and Okudan (2011) also explored the usage of TRIZ tool in the application of lean tools to different functional areas in an industry. More recently, Potter et al. (2019) implemented a TRIZ-based flexible facility design tool that compiled applicable TRIZ principles in an easy to retrieve way while using sector-specific language.

The following sections elaborate on the use of TRIZ in this study, to effectively find solutions for any contradictions that may arise during design for remanufacturing.

3.4. Design Guidelines for Remanufacturing in TRIZ

In the previous section, the usage and applications of TRIZ have been explained in detail. This section elaborates the application of TRIZ to develop design guidelines for remanufacturing. The principles listed in Fig 3-1 and Fig 3-2 summarize the guidelines gathered from literature for this study. Along with the solutions proposed in the original TRIZ matrix, these additional guidelines are added. The methodology is essentially divided into 3 steps:

1. Gathering all the necessary design guidelines for remanufacturing and additive manufacturing from literature.
2. Analyzing several case studies to list out the required features/characteristics required for remanufacturing and forming the features in TRIZ matrix.
3. Providing solutions (design guidelines) to the contradictions in the TRIZ matrix.

3.4.1. Remanufacturing Parameters

In order to identify the features related to remanufacturing, several case studies have been studied and relevant features gathered. The 39 features listed in TRIZ matrix have also been thoroughly studied. Many of the product property features such as ease of separation, ease of cleaning, ease of handling and wear resistance outlined in the Rempro matrix (Sundin et al., 2005) have been used as parameters required for remanufacturing in this study. Design for remanufacturing means designing for each step of remanufacturing, such as design for cleaning, design for disassembly, design for assembly, etc. Hence, the remanufacturing parameters have been developed according to the requirements for DFX, where X is one of the remanufacturing steps. For example, for ease of cleaning or disassembling, the weight, volume, shape, etc., all play a role. Additional parameters such as quality of the part, energy consumed to remanufacture, time consumed to remanufacture, etc. have been gathered from case studies. Some of the TRIZ features have been modified to suit the requirements of remanufacturing parameters. Fig 3-6 shows the mapping of remanufacturing parameters to the original TRIZ parameters.

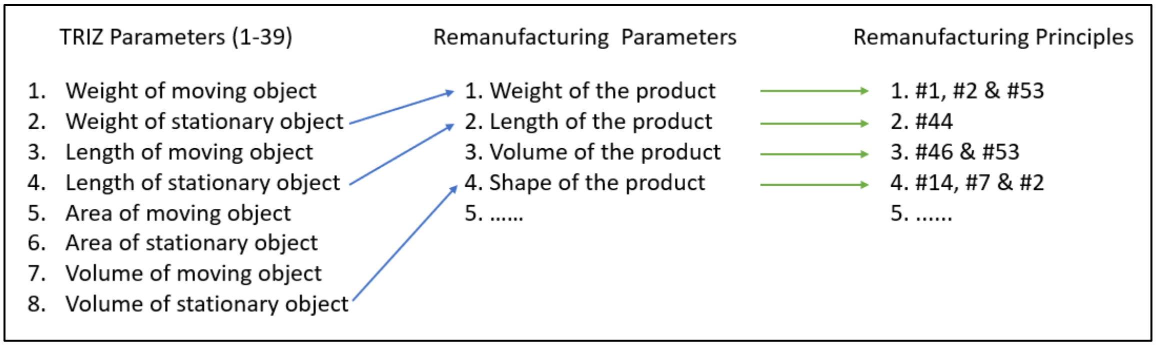


Fig 3-6. Mapping of remanufacturing parameters to original TRIZ parameters

Table 3-3 shows the modifications to the original TRIZ parameters and the corresponding remanufacturing parameters. A total of 12 features have been developed for this study.

Table 3-3. Modification of TRIZ parameters into remanufacturing parameters

Serial No.	TRIZ Parameters	Remanufacturing Parameters
1	Weight of stationary object	Weight of the product
2	Length of stationary object	Length of the product
3	Volume of stationary object	Volume of the product
4	Shape	Shape of the product
5	Loss of energy	Energy consumed
6	Loss of time	Time consumed
7	Ease of operation	Ease of operation
8	Ease of repair	Ease of repair
9	-	Ease of cleaning
10	-	Ease of access
11	-	Ease of separation
12	Measurement accuracy and manufacturing precision	Quality

3.4.2. Remanufacturing Principles

Similar to the original TRIZ matrix, after deciding on the remanufacturing parameters, solutions are presented to the contradictions encountered during practical applications. After a thorough analyzation of the literature available, a total of 48 solutions are presented in this study. Some of the solutions have been taken from the original 40 TRIZ solutions and modified to suit the remanufacturing requirements. Of these, 32 are remanufacturing principles and 16 are additive manufacturing principles. Each of there solutions provided are backed by research studies and case studies. These principles are presented in Fig 3-10a, 3-10b and Fig 3-2 respectively.

Fig 3-7 is the remanufacturing TRIZ matrix, showing the principles for remanufacturing contradictions. Fig 3-8 is the additive manufacturing TRIZ matrix, showing the principles required for remanufacturing using additive manufacturing. Together, both the matrices will give the design guidelines for remanufacturing using additive manufacturing. Fig 3-9 shows the combined TRIZ matrix of remanufacturing and additive manufacturing rules.

#	Improving Feature \ Worsening Feature	Weight of the product (1)	Length of the product (2)	Volume of the product (3)	Shape of the product (4)	Energy consumed (5)	Time required (6)	Ease of operation (7)	Ease of repair (8)	Ease of cleaning (9)	Ease of access (10)	Ease of Separation (11)	Quality (12)
1	Weight of the product	+	1	7	46	19, 15	15, 2	6, 13, 1	2,11	45, 42, 50	45	45, 42	1
2	Length of the product		+		15, 7	6	30, 7	2		1, 41, 50	1, 45	44, 1	
3	Volume of the product			+	7, 2	1, 15		46	1	50	1, 2, 45	44, 48	52
4	Shape of the product		14, 7	7, 2	+	14, 41	14, 17	32, 15, 26	2, 1	41, 43	45, 33, 1	1, 48	
5	Energy consumed	19, 6, 9, 42	6, 7	7		+	32, 7	1		50, 49	51	44, 47, 51, 52	
6	Time required	20, 26, 5	30, 24, 14, 5		17, 41		+	28	1		45, 1	48, 51, 44, 47	
7	Ease of operation	6, 13, 1		46	15	2, 19, 13	28	+	12, 26, 1				52
8	Ease of repair	2		1	1, 2	1, 19	1	1, 12, 26, 15	+				2, 13
9	Ease of cleaning	45, 42, 50, 1	1, 50	50	49, 50	50, 49				+			49
10	Ease of access	45	1, 45	46, 1	45, 1	6, 51	45, 1				+		
11	Ease of Separation	42, 48	44, 1	42	1, 48	44, 47, 51, 52	48, 51, 44, 47					+	51, 52
12	Quality				6	52							+

Fig 3-7. Remanufacturing TRIZ matrix

Improving Feature \ Worsening Feature	Weight of the product (1)	Length of the product (2)	Volume of the product (3)	Shape of the product (4)	Energy consumed (5)	Time required (6)	Ease of operation (7)	Ease of repair (8)	Ease of cleaning (9)	Ease of access (10)	Ease of Separation (11)	Quality (12)
Weight of the product	+			53, 64		61						64
Length of the product		+										58
Volume of the product			+	53, 66		61						
Shape of the product				+	63	63	63		63			57, 63, 68
Energy consumed				53, 66	+		54, 55, 67	62	60	62		56, 57, 62, 63, 64
Time required				53, 66		+	54, 55, 67	62	60	62		56, 57, 62, 63, 64
Ease of operation				59, 64	62, 67	62, 65, 67	+		60	60		62, 63, 64
Ease of repair								+				
Ease of cleaning							60		+			56, 63
Ease of access					62	62	60			+		62, 63
Ease of Separation											+	
Quality					56	56			56			+

Fig 3-8. Additive manufacturing TRIZ matrix

	Improving Feature ↓ / Worsening Feature →	1 Weight of the product	2 Length of the product	3 Volume of the product	4 Shape of the product	5 Energy consumed	6 Time required	7 Ease of operation	8 Ease of repair	9 Ease of cleaning	10 Ease of access	11 Ease of Separation	12 Quality
1	Weight of the product	+	1	7	46, 53, 64	19, 15	15, 2, 61	6, 13, 1	2,11	45, 42, 50	45	45, 42	1, 64
2	Length of the product		+		15, 7	6	30, 7	2		1, 41, 50	1, 45	44, 1	58
3	Volume of the product			+	7, 2, 53, 66	1, 15	61	46	1	50	1, 2, 45	44, 48	52
4	Shape of the product		14, 7	7, 2	+	14, 41, 63	14, 17, 63	32, 15, 26, 63	2, 1	41, 43, 63	45, 33, 1	1, 48	57, 63, 68
5	Energy consumed	19, 6, 9, 42	6, 7	7	53, 66	+	32, 7	1, 54, 55, 67	62	50, 49, 60	51, 62	44, 47, 51, 52	56, 57, 62, 63, 64
6	Time required	20, 26, 5	30, 24, 14, 5		17, 41, 53, 66		+	28, 54, 55, 67	1, 62	60	45, 1, 62	48, 51, 44, 47	56, 57, 62, 63, 64
7	Ease of operation	6, 13, 1		46	15, 59, 64	2, 19, 13, 62, 67	28, 62, 65, 67	+	12, 26, 1	60	60		52, 62, 63, 64
8	Ease of repair	2		1	1, 2	1, 19	1	1, 12, 26, 15	+				2, 13
9	Ease of cleaning	45, 42, 50, 1	1, 50	50	49, 50	50, 49		60		+			49, 56, 63
10	Ease of access	45	1, 45	46, 1	45, 1	6, 51, 62	45, 1, 62	60			+		62, 63
11	Ease of Separation	42, 48	44, 1	42	1, 48	44, 47, 51, 52	48, 51, 44, 47					+	51, 52
12	Quality				6	52, 56	56			56			+

Fig 3-9. Combined TRIZ matrix

The solutions presented are numbered after the 40 TRIZ solutions. That is, rules added to the principles list other than the TRIZ principles have been numbered starting from 41. Fig 3-10a and 3-10b shows the list of remanufacturing principles used in this study. The first 33 principles have been modified from the original TRIZ solutions and the following principles starting from 41, are gathered from the literature.

Number	Principle	Definition
1	Segmentation	Divide an object into independent parts; Make an object easy to assemble; Increase degree of fragmentation
2	Separating or Taking out	Extract the only necessary part of an object; Extract the disturbing part from an object
5	Merging	Bring closer together similar objects; Make objects contiguous or parallel
6	Universality	Make an object perform multiple functions; Eliminate the need for other parts
7	Nested Doll	Place one object inside another; Place multiple objects inside others; Make one part pass through another
9	Preliminary anti-action	Replace actions with counteractions to control harmful effects; Create beforehand stresses in an object
11	Beforehand cushioning	Prepare emergency means beforehand to compensate for the relatively low reliability of an object
12	Equipotentiality	Redesign the object's environment so the need to raise or lower is eliminated
13	The other way around	Invert the action used to solve the problem; Make moveable parts fixed and fixed parts moveable
14	Curvature	Move from flat surfaces to spherical ones; Use rollers, balls and spirals; Go from linear to rotary motion
15	Dynamics	Change the object for optimal performance at every stage; Divide an object into parts capable of movement
17	Another dimension	Move into an additional dimension; Go from single story or layer to multi; Incline an object; Use the other side
19	Periodic action	Instead of continuous action, use periodic or pulsating; Change periodic magnitude or frequency
20	Continuity of useful action	Carry on work without a break; Eliminate all idle or intermittent motion
24	Intermediary	Use an intermediary process; Merge one object temporarily with another
26	Copying	Replace unavailable, expensive, or fragile objects; Replace an object with optical copies
28	Mechanics substitution	Magnetic overhead lifts; Motion sensitive on/off lights

Fig 3-10a. Remanufacturing principles used in TRIZ matrix

Number	Principle	Definition
30	Flexible shells & thin films	Use flexible shells and thin films instead of 3D structures; Isolate the object from its external environment
32	Color changes	Change the color of an object; Change the transparency; Use colored additives or luminescent elements
33	Homogeneity	Objects interacting with the main object should be of the same material
41	Reduce Sharp Corners	Avoid sharp corners in designs unless absolutely necessary. Have curved or chamfered corners preferably
42	Single Direction	Make sure all the joints can be disassembled from a single direction
43	Avoid close spaced horizontal projections	Avoid having spaces in between parallel projections. Have inclined surfaces, which make the area in between more accessible.
44	Avoid long disassembly paths	Longer disassembly paths are more demanding and might lead to changing place or awkard positions ,which are time consuming
45	Pre-Design for easy access	Hard to access parts might consume more time, special tools to disassemble or might even damage the part
46	Hollow structures	To reduce weight of object and make it easy for handling, use hollow structures
47	Reduce the number of operations performed	Design for multiple detachments with one operation. This way, the number of time a task is done will be reduced saving time.
48	Avoid permanent joints	Use of threaded fastners or breakable snap fits or shape memory fastners facilitates disassembly
49	wear resistance	Resistance of th epart agaisnt wear and tear
50	Smooth surface	A surface that is perfectly regular and has no holes, lumps, or areas that rise or fall suddenly - Cambridge Dictionary
51	Mark/Eliminate hidden joints	Hidden joints are hard to see and access.
52	mark testing points	NA

Fig 3-10b. Remanufacturing principles used in TRIZ matrix (continued)

Overall, this chapter details the means and methods used to develop design guidelines for remanufacturing using additive manufacturing. The tool used (TRIZ) has been explained in detail and the developed matrix has also been presented. The 12 contradictions and their relatability to original TRIZ contradictions, and the 48 principles developed for this study have been explained. In the following chapter, the usage of the presented TRIZ matrix will be elaborated through a case study.

CHAPTER 4

CASE STUDY

4.1. Introduction

This chapter explains the usage of the developed TRIZ matrix with the help of a case study. Section 4.2 talks about the means and methods used for the case study. Section 4.3 elaborates on the case study. Section 4.4 provides more examples on the applications of TRIZ for remanufacturing. Section 4.5 provides a comparison of the case study with a laser additive manufacturing study.

4.2. Methods and Means

The material used for this case study is ABS and the machine used is an IIIP Monoprice 3D printer. This study could not be done using a metal 3D printer on a metallic sample due to cost and time constraints.

4.2.1. Machine

The IIIP printer consists of a base plate, nozzle head, material spool holder and a control box. The distance between the tip of the nozzle and the base plate can be adjusted using the screws below the base plate. Fig 4-1a shows a picture of the IIIP Monoprice printer. This machine offers print capabilities for two materials namely, ABS and PLA. The material comes in spools of wire (shown in Fig 4-1b), which can be hung on to the spool holder at the top of the machine. This material wire is fed into the nozzle head and the base plate and nozzle are preheated to the required temperatures before giving a print. The machine has an SD card port, into which the designs needed for printing can be uploaded and printed.

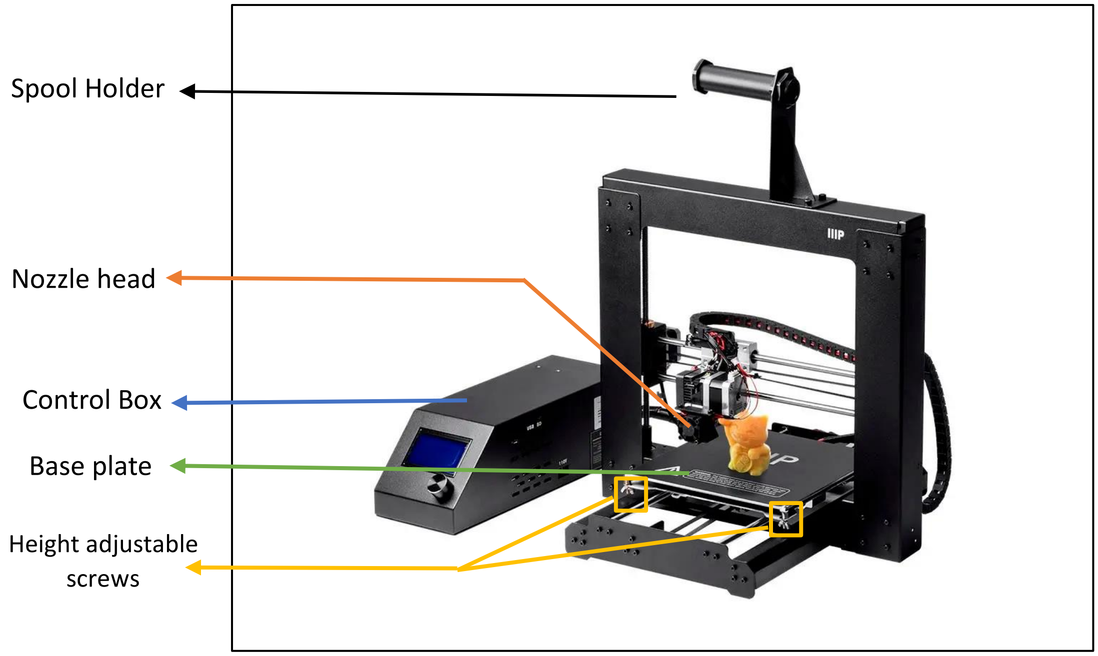


Fig 4-1a. An IIIP Monoprice Printer (Monoprice.com)

Fig 4-1b. Material spool for IIIP printer (Monoprice.com)

4.2.2. Material

The material used, ABS, also known as Acrylonitrile butadiene styrene, is a thermo plastic. There is no particular reason for using the material for this case study. Since ABS is amorphous, it does not have an exact melting point (creativemechanisms.com). The melting temperatures used by IIIP Monoprice printer for ABS is 250 degree Celsius. The base plate is also heated up to a temperature of 95 degree Celsius to ensure proper adhesion of the material to the base.

4.2.3. Slicing Software Cura

3D printers cannot print with a solidworks model of the part. They need a slicing software to slice the part and use this model for printing. The slicing software used for this machine is Ultimaker Cura 4.2.1., a free slicing software available online and hence very accessible. The type of printer being used can be added into the settings of Cura, so that the dimensions of the 3D printer (the base plate) are accurate. This way, Cura notifies if the part exceeds the size of the build plate, or the capacity of the printer. The printer used for this study comes under the category of Prusa i3. Cura basically has 3 sections – Prepare, Preview, and Monitor. In the Prepare section, there are many features to apply to the print. A vast material selection is provided to be compatible with the kind of printer that is being used along with it. The layer thickness, shell thickness, infill density, infill pattern, material being used, etc. are some of the features that can be changed according to the print quality and quantity desired by the user. All the features in Cura are listed in Table 4-1. Similar to any 3D printer, for a faster print, the travel speed and layer thickness need to be increased and vice versa for a better-quality print.

Table 4-1. Cura features and options available to prepare print

CURA FEATURES	OPTIONS AVAILABLE
Quality – smaller the layer height, better is the quality of the print.	Layer height
Shell – It is the wall thickness of the print outside of the raster area.	Wall thickness, top/bottom thickness
Infill – Infill is the part inside the shell, that needs to be filled. The density and pattern of infill can be varied depending upon the requirements.	Infill density, infill pattern
Material – Cura is compatible with many materials. It has the temperature at which the material and build plate should be for a good print.	The printing temperature and build plate temperature
Speed – The speed with which the nozzle head traverses is called print speed. It can be changed depending upon the material and print quality.	Print speed
Cooling - The cooling of the nozzle can be adjusted by changing the cooling fan speed	Enable print cooling, fan speed
Support - This feature allows one to adjust the placements of support structures.	Support placement, support overhang angle

The second section of Cura, Preview, provides the sliced version of the model. In the preview version, it shows any support structures that might be used and how the build process will go while printing. One of the cool features of Cura is that, at any given height of the part, the traversing path of the nozzle can be viewed. The estimated print time is also provided. Depending upon the user's requirement, the build features can always be changed to decrease or increase the build time. Once the user is satisfied with the estimated time, the model can be uploaded into the printer for printing. Fig 4-2 shows a screenshot of the preview section of Cura.

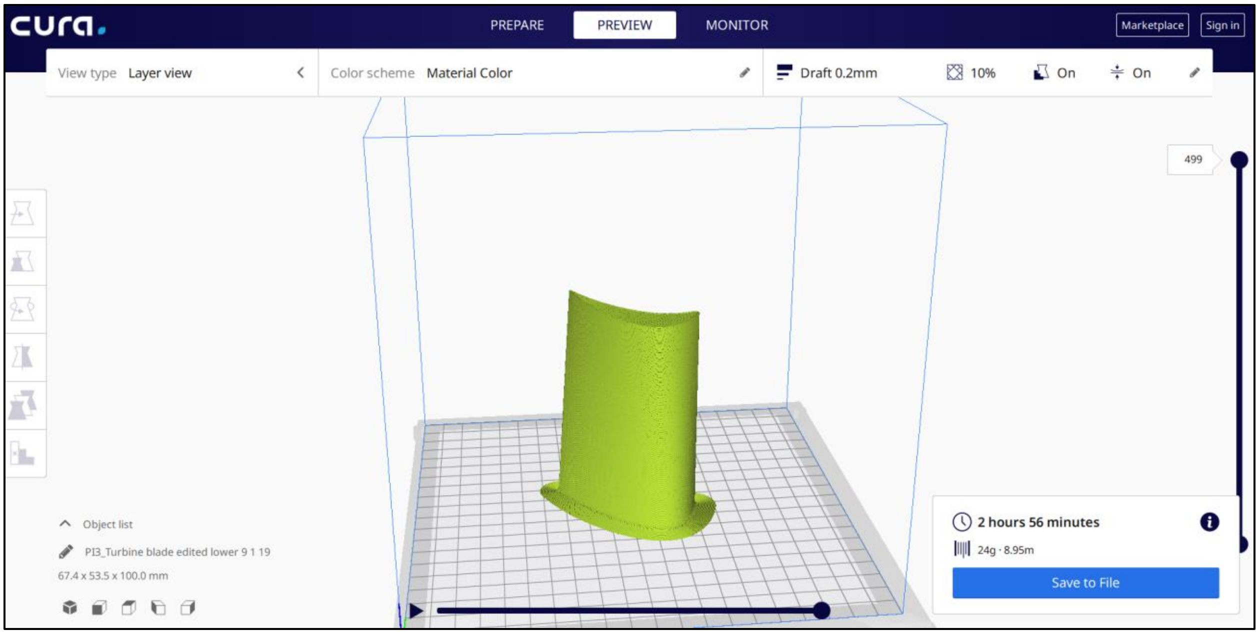


Fig 4-2. Preview section of Cura showing a sliced turbine blade portion

The third and last section of Cura is the monitor phase. If the print is given by connecting the computer to the 3D printer, the print progress can be viewed in this section. But if the sliced model is copied into an SD card and printed, this section does not provide any information. In this case study, the sliced model has been copied to an SD card and printed.

4.3. Case Study Procedure

This case study is of two parts – applying the TRIZ matrix developed to a remanufacturing problem and then actually demonstrating the remanufacturing application. Section 4.3.1 explains the TRIZ application and section 4.3.2 describes the experimental setup and process for conducting the case study.

4.3.1. TRIZ Application

TRIZ can be applied to any type of problem. For the purpose of this case study, a turbine blade remanufacturing has been considered. Everyday objects such as refrigerators, AC compressors etc., can be remanufactured. However, due to their volume, they have not been considered for this case study. Everyday objects such as volume button in car, mobile phones etc., can also be remanufactured. A car volume button can be 3D printed and used, instead of trying to fix a broken volume button and it is not a costly object. Remanufacturing of phones is a challenge for the phone manufacturing companies. It is very hard to collect used phones and thus a company cannot rely on getting a set number of phones every cycle (Hatcher et al., 2013). It is not easy to remanufacture phones personally because not everyone will have the means and methods to achieve the level of accuracy and precision required.

To apply the design rules in TRIZ, the remanufacturing case is studied closely. Wilson et al. (2014) have explored the use of additive manufacturing technique – laser direct deposition – in the remanufacturing industry by remanufacturing a turbine blade. Turbine blades are often very expensive and difficult to manufacture, making them very suitable for remanufacturing. Fig 4-3 shows the image of a broken turbine blade. This broken part is reconstructed through an additive manufacturing technique. For the present case study, the blade is assumed to be wornout instead of broken. Using the developed TRIZ matrix, the necessary design guidelines can be identified as follows. Since a broken blade is being fixed, the weight, volume or shape of the object are not changed. Given the small size of a turbine blade, handling of the part is also not an issue. The TRIZ features of concern are the energy consumed, time required to print the broken part and the overall quality of the part.

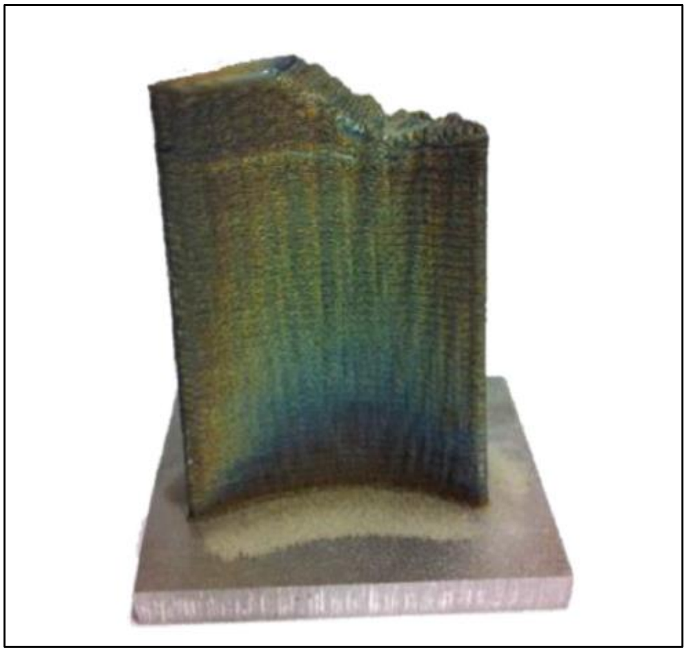


Fig 4-3. Image of a broken turbine blade (Wilson et al., 2014)

Thus, from the TRIZ matrix, the rules to change (decrease) the time and energy consumed for remanufacturing the part, while preserving the quality are 56, 57, 62, 63 and 64. The rules are stated below:

56 – Reduce the staircase effect by choosing an adequate part orientation.

57 – Design optimization for better quality

62 – Gaps between round features, vertical orientation, and manufactured parts. Gaps should not be below specification.

63 – Reduce gap areas. Design the gap areas as small as possible to reduce powder adhesion.

64 – Use cavities to reduce the volume to be exposed and to reduce the weight of the part.

As the turbine blade weight or volume is not affected, rule 64 is not suitable. Rules 57, 62 and 63 are associated with design changes, which are not relevant to the present case study. Rule 57 is the most relevant one applicable to this study. Hence the orientation of the part should be chosen such that the staircase effect is minimized to preserve the quality while reducing the time and energy consumed. To satisfy these conditions, the part should be oriented in vertical direction. In this orientation, there will be no need for support structures, making handling of the part easier. With the staircase effect at a minimum in vertical orientation, the quality of the part will also be preserved.

For the above example, the TRIZ matrix ensures that all the necessary features/parameters required for remanufacturing are being considered and provides the necessary guidelines and/or solutions to reach those parameters, such as maintaining the correct orientation for better quality. It is possible to approach this solution without the TRIZ by going through research papers and finding proper design guidelines. This approach would not only be very time cosuming, but also incomplete in trying to identify all the interdependencies between different features and parameters.

4.3.2. Experimental Setup

Due to time and financial constraints, an actual metal 3D printer could not be used for this case study. Hence, to demonstrate the usage of the developed TRIZ matrix, an IIIP Monoprice 3D printer has been used. A model of the turbine blade has been designed using SOLIDWORKS 2019 software. For the purpose of this case study, a worn-out turbine blade is assumed. The direction of wear is assumed to be horizontal. In order to create this worn-out section, the original model of the turbine blade has been sliced off by 10mm from the top. This sliced off part is the worn-out region. This particular wear out is also assumed to be flat. If not, the surface can always be ground so that it becomes a flat surface. This step might not be required if the reprinting is done using laser metal AM techniques. But for an FDM printer, it is important for two reasons:

1. The nozzle head of an FDM printer is large and cannot fit into cross sections that might obstruct the movement of the nozzle head. For a laser printer, the laser beam can reach anywhere on the surface of the part/layer. Fig 4-4 shows the nozzle head of an IIIP Monoprice printer.

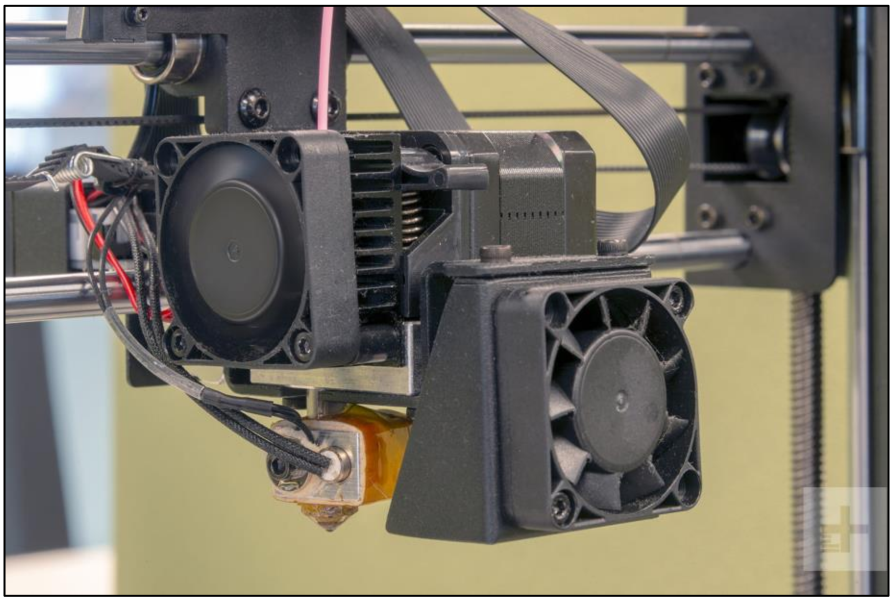


Fig 4-4. Nozzle head of an IIIP printer (digitaltrends.com)

2. Having a flat surface to lay material upon, will help in better adhesion of the new layers to the existing part.

Fig 4-6 shows the solidworks model of the turbine blade design used for this study. This model has been taken from the Grab-CAD library (GrabCad, 2019). The lower part of the turbine blade has been printed off first. This lower part represents the worn-out turbine blade. The upper portion of the blade was printed on top of this. However, after the first attempt, it was observed that the lower and upper parts did not align properly even though both the parts had the same starting coordinates (location) in Cura. This is attributed to the fact that the turbine blade cross-section is not uniform. The blade twists at a certain angle along its length. Fig 4-5 shows the top view of the turbine blade, in which this angular displacement of the blade can be seen clearly. In Fig 4-5, the blue line shows the lower section of the blade, whereas the orange line represents the topmost layer. As a result, even though the base of the lower part of the turbine blade was at (0,0) coordinates, its topmost layer's coordinates were not the same. Hence, giving the location for the upper portion of the turbine blade as (0,0) did not align the upper part with the lower portion. Measuring this angular change in the turbine blade and locating it on the base plate of a 3D printer has been very challenging with the means available.

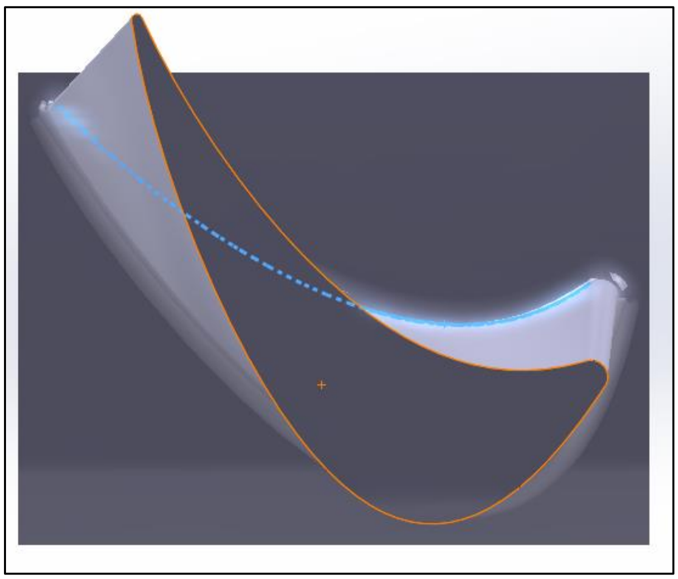


Fig 4-5: Top view of the turbine blade, showing the twist in the blade.

To counter this issue and make sure that the part is aligned, a square section has been modeled around the turbine blade as a reference frame as shown in Fig 4-7. This version of the turbine blade along with the reference frame has been sliced to create the worn-out lower portion and the upper portion of the turbine blade. Fig 4-8a and 4-8b show the upper and lower portions of the turbine blade. The lower part of the turbine blade is 100mm in height and the upper portion is 10mm in height. However, to reduce the estimated print time of 13hrs, the model has been proportionally reduced by 75% in size (in Cura) to decrease the print time to 7 hrs 13 mins. The lower part of the turbine blade is printed off first. The Solidworks model is saved as an STL file. The slicing software used is Ultimaker Cura 4.2.1. This STL file is exported into the Cura environment and is sliced into layers (based on the layer thickness selected) for the print.

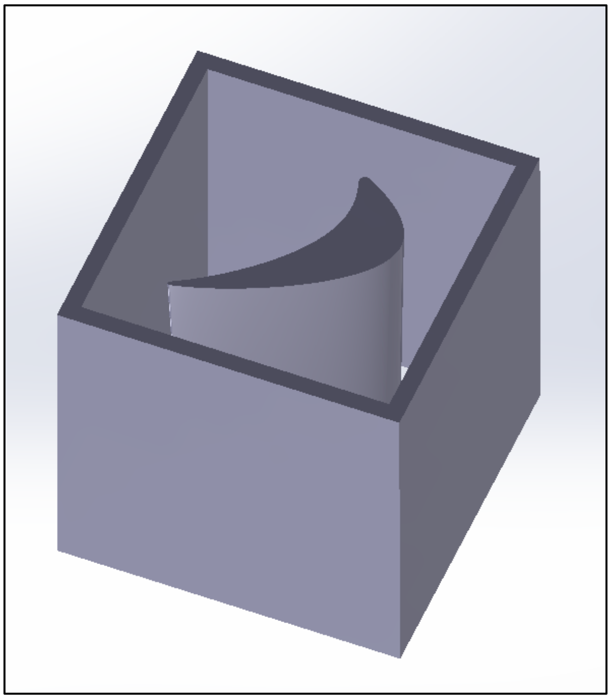


Fig 4-7: Turbine blade with the reference frame

The settings used to print this file are as follows:

1. Infill Density – 10%
2. Cooling fan speed – 80%
3. Travel Speed – 40mm/sec
4. Materials used – ABS
5. Layer thickness – 0.2mm

Fig 4-9 shows the sliced version of the turbine blade in Cura.

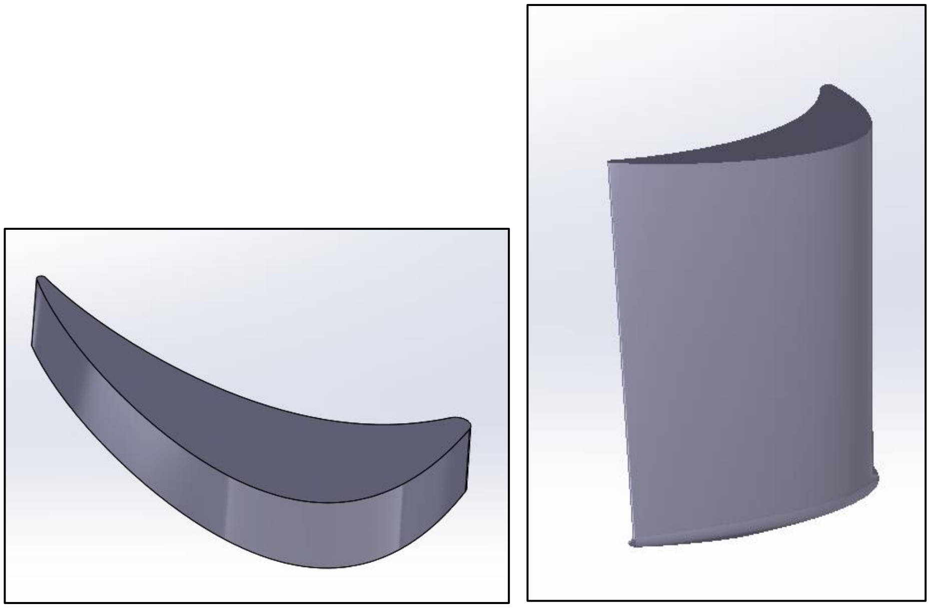


Fig. 4-8a and 4-8b: Solidworks model of the upper and lower portions of a broken turbine blade.

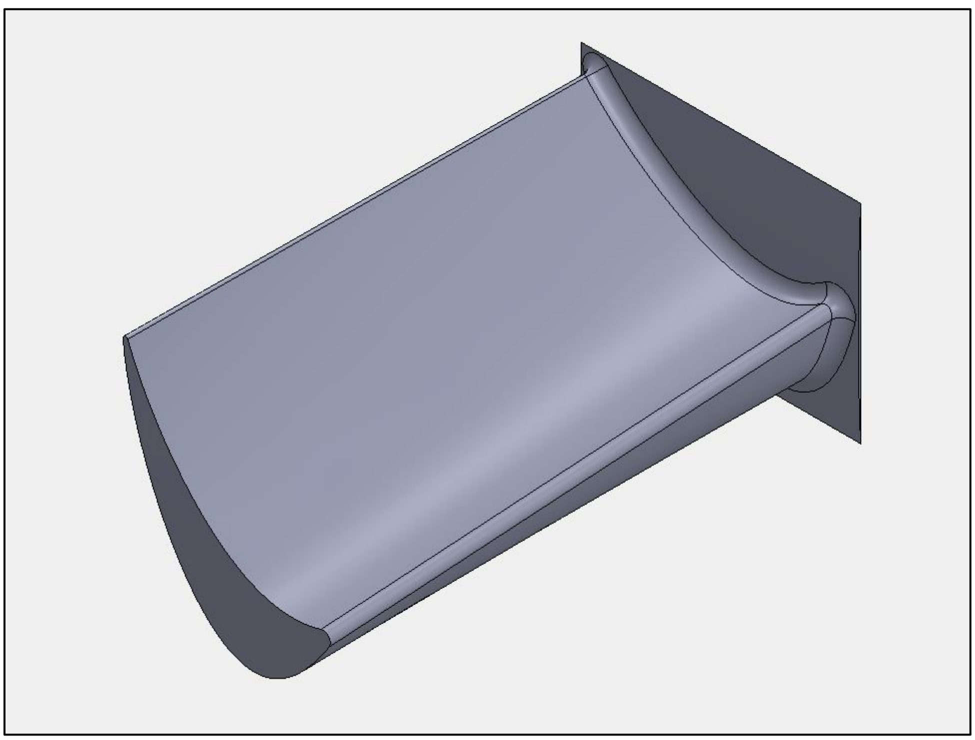


Fig 4-6: Solidworks model of the whole turbine blade.

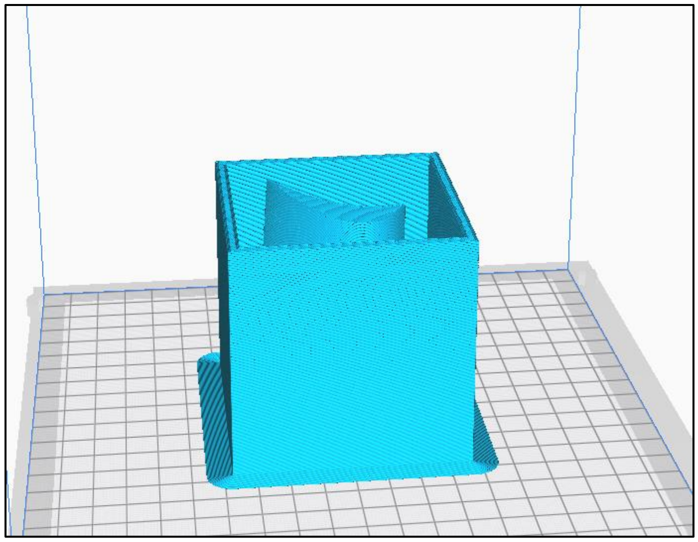


Fig 4-9: Sliced model of the turbine blade in Cura

As can be seen from Fig 4-9, no support structures were needed for the print. The general speed requirement of the nozzle head for an IIIP Monoprice printer is 60mm/s, usually used with PLA material. However, for this case study, ABS material is being used, which has a higher melt temperature than PLA. Hence the travel speed and cooling fan speed have been reduced to make sure there is enough time for the material to reach its melt temperature. Once the settings have been updated, the model is sliced in Cura and is imported to the SD card provided along with the printer. Before giving the print, it is made sure that the material spool is fed into the nozzle. The nozzle and bed are pre-heated to a temperature of 250-degree Celsius and 90-degree Celsius, respectively. Once the temperatures are reached, the print begins. Fig 4-10 shows the printed lower part of the turbine blade along with the reference frame. The top surface has been sanded with sandpaper for a flat surface, to ensure proper adhesion of the upper part of the turbine blade.

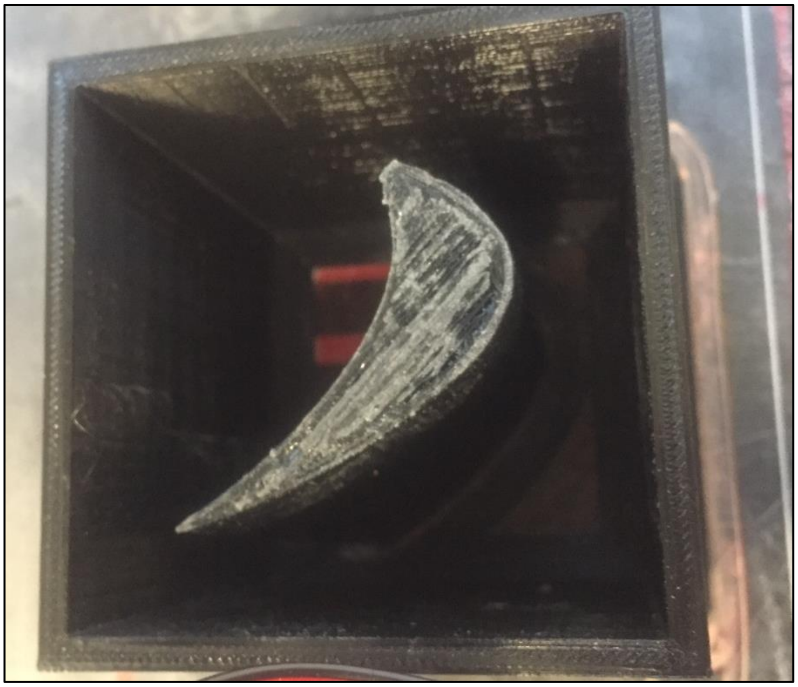


Fig 4-10: 3D printed lower part of turbine blade along with reference frame

4.3.3. Procedure

One the lower part is printed, the next step is to print the upper portion on top of it. The location of print is marked on the print bed before the part is removed. The support material surrounding it is not removed yet, as it might be required to stick the part to the base plate while printing the upper portion on top of it. In order to be able to print on top of an existing part, the Z-axis needs to be offset to the height of the part. The IIIP printer locates its nozzle head by using X, Y and Z axes switches. Once these switches are clicked, the nozzle head stops moving, indicating that it is in the home position. Fig 4-11 shows the Z-axis shaft and the control switch.

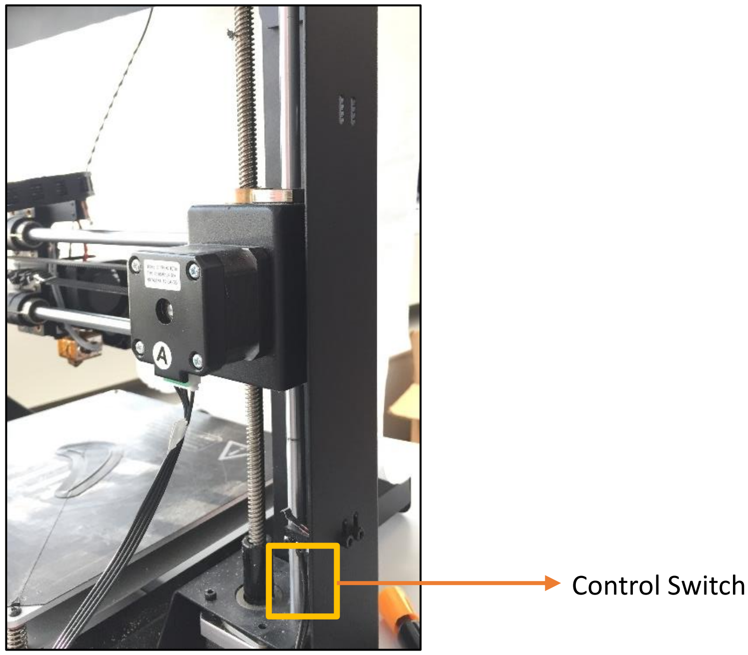


Fig 4-11: Z-axis shaft and control switch in IIIP Monoprice printer

To offset the Z-axis location, a 3D printed V-block, shown in Fig 4-12 has been used. The V-block has a groove (see Fig 4-15) which is fitted to the Z-axis shaft so that the home position of Z is offset by the height of the V-block. Because of this V-block, the Z-axis switch is clicked while the nozzle is still at a certain height, making the offset position as its home position. The V-block is equivalent to the height of the lower turbine blade, thus ensuring the upper portion starts printing on top of the bottom part.

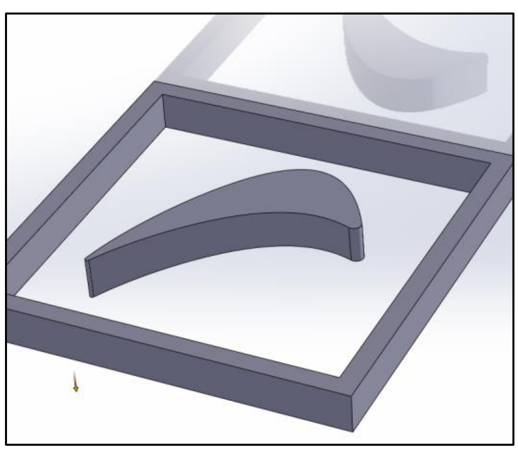


Fig 4-13: Solidworks model of the upper turbine blade along with reference frame

The Solidworks model of the upper turbine blade (shown in Fig 4-13) is saved as an STL file and exported to Cura slicing software. Here it is sliced with similar settings as for the lower portion and copied on to the SD card. The lower part of the turbine blade is glued to the base plate with the help of the marks on it to make sure it is at the center of the build plate. The upper part of the turbine blade is also made sure to be at the center of the build plate in Cura software. Once the nozzle and the base are pre-heated to their required temperatures, the upper part of the turbine blade starts printing. Since this is a new print for the printer, it starts laying down the support material as well. However, since the print is on top of another part, the support material is not needed. A thin sheet of paper has been used to collect all the support material printed for this part, as shown in Fig 4-14. Once the part printing starts, this paper is removed, thus ensuring the support material does not create a mess.

Fig 4-14: Sheet of paper used for collecting support material for upper part print

Fig 4-12: 3D printed V-block to offset the Z-axis

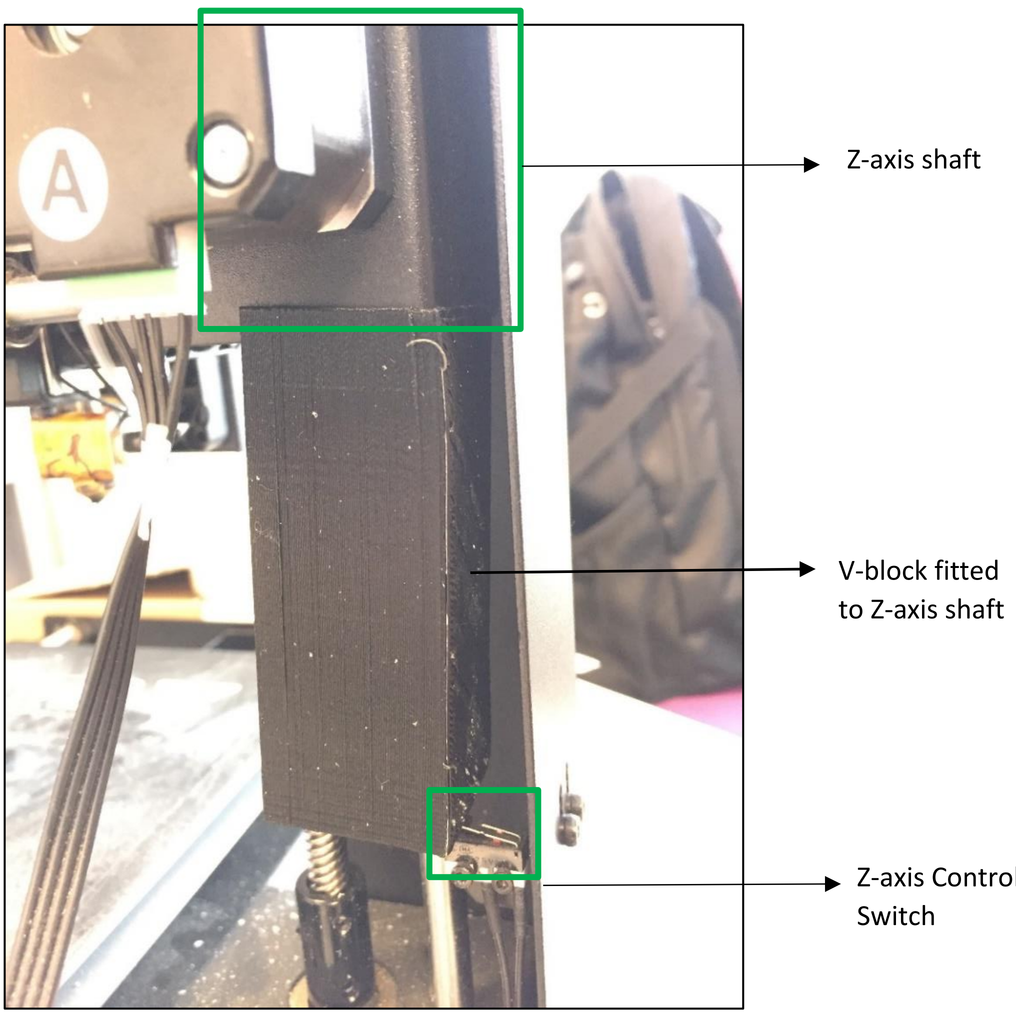


Fig 4-15: V-block offsetting the Z-axis by hitting the Z-axis switch beforehand

Applying rule 57, the orientation of the print is chosen such that the quality and energy consumed to print would be minimum. In the vertical position, the height of the part (upper part) to be printed is small compared to printing in a horizontal direction. Also, in the horizontal direction, the adhesion of the new layers to the existing part will not be good, as the layers do not completely touch along the surface. However, in the vertical orientation, the new layer is directly laid on top of the surface of the existing part. This ensures proper adhesion of the new layers to the bottom part. Fig 4-16a and 4-16b show the difference between horizontal and vertical printing of the part.

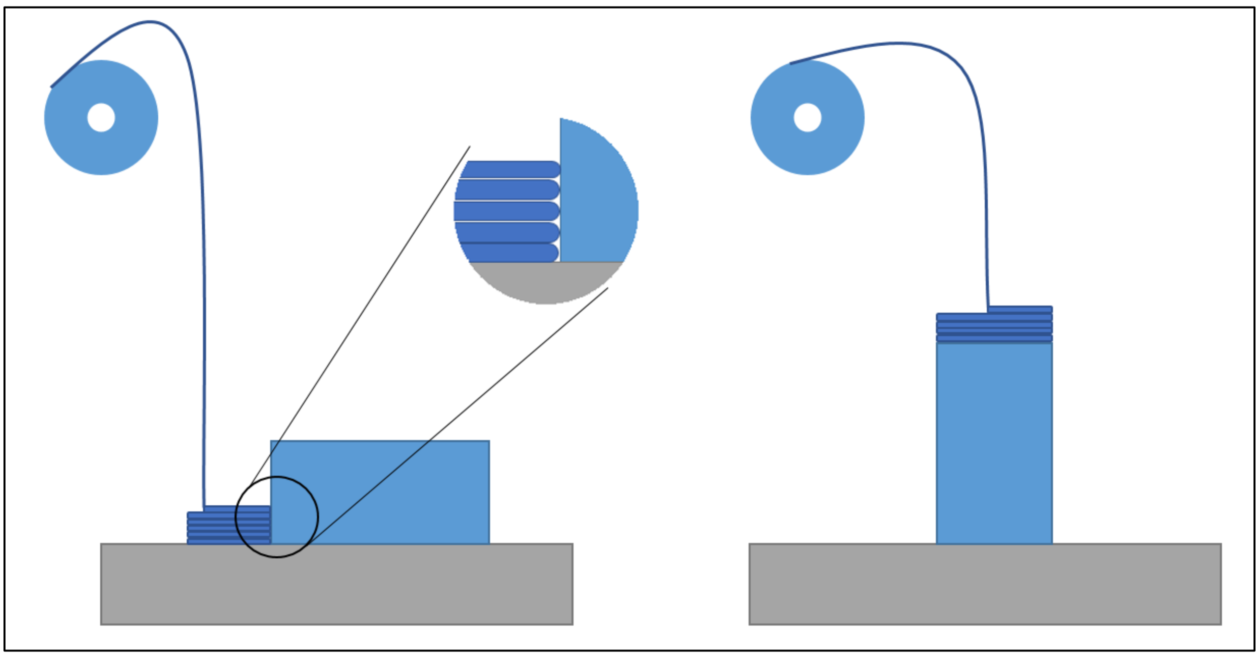


Fig 4-16a and 4-16b: Picture depicting horizontal print orientation and vertical print orientation for the current case study

Once the print is complete, the part is removed, and the support structures are scrapped off. Fig 4-17 shows the remanufactured turbine blade with its reference frame. It can be seen from the figure that there is a slight offset between the upper and lower parts of the turbine blade and frame. This will be discussed further in the following sections, where the limitations of this case study are addressed.

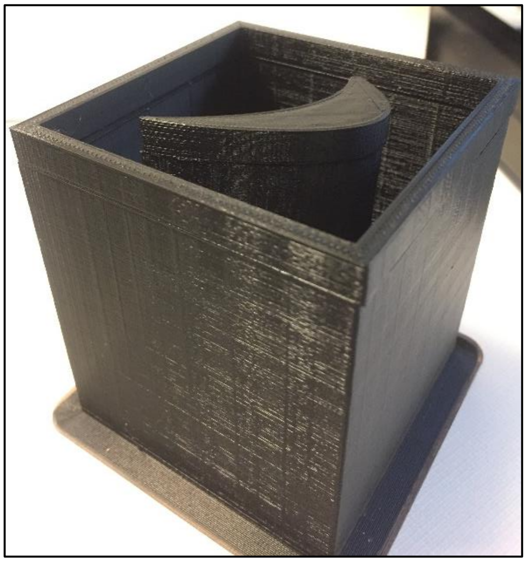


Fig 4-17: Remanufactured turbine blade along with reference frame

Thus, using the developed TRIZ matrix, a turbine blade is remanufactured. The following section provides a few more examples where TRIZ matrix can be applied to remanufacturing using additive manufacturing.

4.4. Remanufacturing Examples

The previous section explained about a single remanufacturing case study. However, to understand the TRIZ tool better, some more remanufacturing examples need to be studied. This section provides such examples that help in understanding the tool better.

4.4.1. Fuel Tank Design Change

A major issue with fuel tanks is the fuel tank shavings, that accumulate in filters over the course of time. These shavings are hard to be removed as they need to be flushed out from a closed fuel tank. However, this cleaning of the fuel tank is also not as effective as expected because these shavings might often move into the sharp corners of the fuel tanks and settle there. Therefore, they might not be completely removed even during the cleaning phase. To counter this problem, one solution is to modify the fuel tank design such that shavings cannot get accumulated. In order to do this, the mold of the fuel tank needs to be changed. The lower portion of a fuel tank mold design is shown in Fig 4-18. As molds are extremely expensive and costly, it is best to remanufacture these molds.

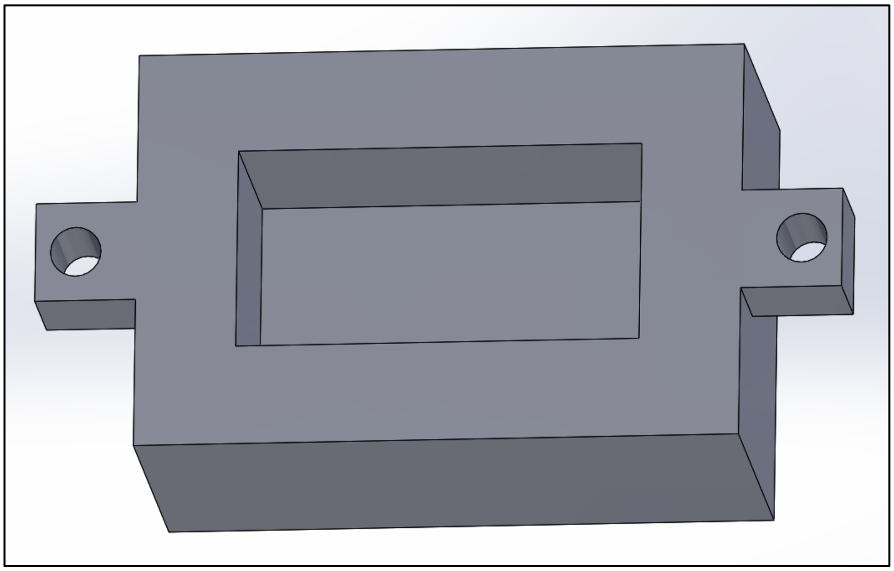


Fig 4-18. Bottom mold section for a fuel tank

For the present case, using the TRIZ matrix, the features involved would be ease of cleaning, energy consumed, the time required and quality of the part. The ease of cleaning of the part should be improved, the time and energy consumed should be decreased/preserved and the quality of the part should be preserved. The applicable rules for this are 49, 50, 56 and 63. Here we also must change the shape of the part to increase ease of cleaning. For that, rules 41, 43 and 63 are applicable. All the relevant design rules are as listed below:

41 – Reduce Sharp corners

43 – Avoid close-spaced horizontal projections

49 – Resistance of the part against wear and tear

50 – Smooth surfaces reduce the effort required to clean

56 – Reduce the staircase effect

63 – Reduce Gap areas

Of the above-mentioned rules, 43 is not applicable as the concerned mold design does not have any projections. The wear resistance of the part can be improved by laying a superior wear material while repairing or changing the design of the part. Here we can use rule number 41, to reduce sharp corners, which is the primary reason for the fuel shavings being stuck in the fuel tank. This can be done by adding more material to the corners of the mold using additive manufacturing. Fig 4-19 shows a sample design of fuel tank mold after reducing sharp corners using additive manufacturing. Rule number 56 can be used to reduce the staircase effect, thus preserving the quality of the part. After the AM process, proper surface finish ensures that the mold gets a smooth surface, thereby ensuring a smooth surface for the fuel tank too, which makes cleaning easier.

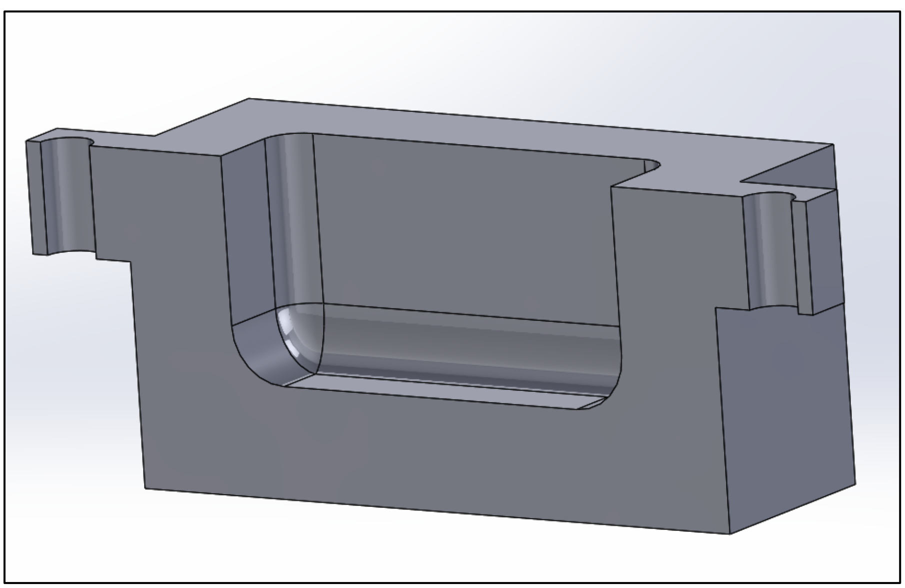


Fig 4-19: Cross-section of fuel tank mold with reduced sharp corners

For the above example, the TRIZ matrix ensured that all the necessary features/parameters required for remanufacturing have been considered. Without the TRIZ matrix, one will not have a structured approach to solve the issues. One could focus on quality of the part and the other on ease of cleaning, while compromising the other. However, with the help of TRIZ, the contradicting features are also preserved with the solutions provided.

4.4.2. Remanufacturing of Tires

A tire has 2 parts – the threads, and the core. The threads of the tire are the ones that usually get worn out, but the core of the tire is usually in good shape and can be reused (mobiusenviro.com). For remanufacturing tires, the TRIZ features that would need to be preserved (or decreased) are the quality of the part, shape of the part, energy consumed, and time required, while increasing the ease of repair of the part. Considering these features, the applicable TRIZ rules are 1,2,19 and 13. These rules are as stated below:

1 – Segmentation: Divide an object into independent parts; Make an object easy to assemble; Increase the degree of fragmentation

2 – Separating or taking out: Extract the only necessary part of an object; Extract the disturbing part from an object

13 – The other way around: Invert the action used to solve the problem; Make moveable parts fixed and fixed parts moveable

19 – Periodic Action: Instead of continuous action, use periodic or pulsating; Change periodic magnitude or frequency

In the above-mentioned rules, rule-1 is not applicable to the current situation as we do not have any independent parts in a tire. Rule-2 can be applied by extracting the necessary part of the tire – which is the core. Rule 13 is not applicable as there are no parts/actions that can be inverted in the remanufacturing process. Similarly, rule 14 is also not applicable to the current situation as there are no periodic actions that will be required while remanufacturing tires. Hence the only applicable rule is Rule-2. Thus, a tire can be striped of the used threads and the core of the tire can be reused. Remanufacturing of tires is like newly manufacturing a tire except that the core of the tire is re-used (mobiusenviro.com).

4.5. Remanufacturing Using DED Vs FDM

Wilson et al. (2014) have studied the remanufacturing turbine blades by laser direct deposition method. An Optomec LENS 750 machine and stainless steel 316L powder were used for the study. The reconstruction of damaged geometry and alignment of the turbine blade for the print are compared with the current case study in the below sections.

4.5.1. Reconstruction of Damaged Geometry

In contrast to the current case study where the damaged surface is assumed to be flat, Wilson et al. have assumed a broken structure as shown in Fig 4-3. In order to regenerate the broken surface, prominent cross-section (PCS) technique was used. The defective turbine blade was scanned and transformed into a meshed surface with triangular facets. This meshed surface was transported into CATIA^{TM} V5 software, where the damaged part was reconstructed with the help of splines and PCS algorithm.

4.5.2. Alignment of Damaged Turbine Blade

Wilson et al. (2014), have used a tool path software, which generated a geometric bounding box. Fig 4-20 shows the bounding box and the broken turbine blade image. In the present case study too, a bounding box section has been used to align the bottom and top parts of the turbine blade. However, the accuracy of the tool path generation is much higher for the Wilson et al's turbine blade case study and the deviation was within the acceptable limits of the aerodynamic industry. In the present case study, the deviation is more than 1mm, which is out of tolerance as per the industry standards.

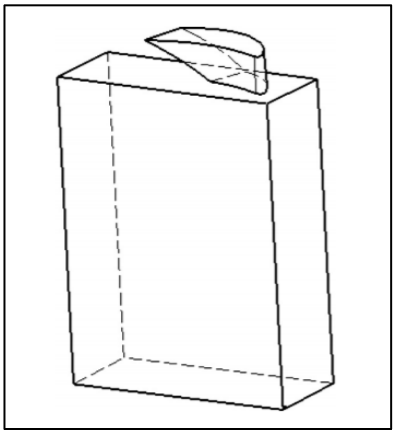


Fig 4-20: Bounding box used for remanufacturing the turbine blade (Wilson et al., 2014)

4.6. Summary

In conclusion, this chapter explains about the application of the developed TRIZ matrix and explains it with the help of three cases. One of the case studies has been implemented and studied. The means and methods, materials and equipment used for the case study are explained in great detail. The limitations of the present case study have also been discussed. In the following chapter, the limitations of the developed TRIZ tool and the methods used for the case study are explained. The scope for future work is also discussed.

CHAPTER 5

RESULTS AND DISCUSSION

5.1. Introduction

So far, a TRIZ matrix has been developed for providing design guidelines for remanufacturing using additive manufacturing and its implementation has been explained with a case study. This chapter discusses the limitations of the case study and Monoprice 3D printer, limitations of the TRIZ tool developed, troubles with additive manufacturing and the scope of future work for this study.

5.2. Limitation of Case Study

This section talks about the limitations of the case study used to demonstrate the use of the TRIZ matrix. One important limitation is that FDM printers are not compatible for remanufacturing of parts. This is because of two reasons:

1. Since the FDM printer is a plastic printer, it cannot be used with metals. Unfortunately, many parts that need to be remanufactured are metallic parts, thus limiting the use of an FDM printer for this application.
2. The size of the nozzle head in an FDM printer is very large. Even to remanufacture a plastic part, the nozzle tip might not always reach into the corners or the part to lay material where ever required, to repair the part.

These issues will not arise in metal 3D printers such as SLM or DED because, firstly they are meant for metals and second, these printers use a laser beam to melt and lay material. A laser can be very thin and focused, thus being able to reach into corners that bulky nozzle heads can never reach. Hence, remanufacturing is much more effective and practical on those machines.

Another limitation of this case study is that there is a slight offset between the upper and lower portions of the turbine blade. Even though the location settings in Cura have been at the same place (0,0), the print was offset by about a millimeter. The suggested hypothesis is that the locating method/system of an FDM Monoprice printer is not precise enough to such degrees of measurement. In comparison to an FDM Monoprice printer, SLM or DED printers would not have this issue, as observed from Wilson et al's. (2014) case study.

5.3. Challenges of Implementing AM Techniques for Remanufacturing

Though additive manufacturing and remanufacturing concepts have been around for nearly three decades, they are not used up to their full potential. There are two reasons for this. First is the unfamiliarity and complexity of remanufacturing. The challenges and limitations faced for remanufacturing of parts have already been discussed section 2.3 "Barriers to Remanufacturing." The second reason is the challenges faced to integrate additive manufacturing techniques into the industry. Coykendall et al. (2014) have identified five main challenges of integrating AM techniques into industries, either for production or remanufacturing. These challenges are listed below:

1. Size limitations: The size of an additively manufactured part can be only as much as the machine allows for it. If a bigger part needs to be printed, the size of the AM machine should be bigger than that part.

2. Scalability limitations – In the present world, it is quite common for industries to increase or decrease production as determined by the market conditions. But with AM machines, it is hard to increase or decrease the rate of production as the time required to print a part is the same (Five challenges with the additive manufacturing in the aviation industry, 2018).
3. Narrow range of materials and high material cost – The type of materials used of AM machines are quite limited. They are polymers or a few metallic powders. This limits the range of applications for which AM can be used.
4. Limited multi-material printing capability – Very few printers are capable of using multiple materials at the same time to build a part. It would be very beneficial to have this feature on a wide range of machines.
5. Quality Consistency – 3D printed might have inconsistent defects that appear only on a specific part. Sometimes a defect like warping might be an issue for one sample, but might not for another. This makes the consistency of quality a challenge in 3D printed parts.

As a result of these challenges, additive manufacturing has not yet paved its way into mass production facilities.

5.4. Limitations Of The TRIZ Tool

Though the developed TRIZ matrix is very beneficial and useful, it has its own limitations. Firstly, the matrix does not help determine how beneficial it is to remanufacture a component. It only provides the steps/guidelines once a part has been decided to remanufacture but not during the decision process.

Secondly, the TRIZ matrix provides the techniques that can be used to remanufacture a product more efficiently but does not explain those techniques. For example, it directs the user to choose the orientation of the part appropriately while 3D printing but does not tell what the orientation should be. This is because the orientation varies from part to part and cannot be generalized for all the parts.

Finally, the TRIZ matrix is a tool that is simple enough to use but not self-explanatory. The user needs to know what a TRIZ tool is and how to use it. Though this is not a major limitation, for a layman, this could be a hindrance to using the tool effectively.

5.5. Conclusion

So far the limitations of the case study, the TRIZ tool developed and the challenges of implementing AM in industries have been addressed in this chapter. This section explains the uniqueness of this study and talks about the scope of future work.

5.5.1. Contributions of This Research

This study is unique in the fact that it provides a coherent structure of design rules in the form of a TRIZ matrix. There are many studies/case studies that use additive manufacturing for remanufacturing, but they only focus on that specific issue, whereas this study provides a general guideline for the same. With the help of this TRIZ matrix, one can easily identify the pivotal parameters for their study and identify the necessary guidelines as required.

5.5.2. Scope of Future Work

Building on to the limitations section, this section provides the details of future work that can be done to expand the study. The cases for remanufacturing a part considering its life cycle use, cost benefits, and environmental impacts can be studied to include the conditions for remanufacturing a part. This information then would provide the user with a complete TRIZ guide to remanufacturing.

The TRIZ matrix could be developed further by including all the means and methods used for remanufacturing. That is, the techniques used for cleaning parts, changing the shape, etc., could be further elaborated and included in the matrix.

Overall, this study has developed a TRIZ matrix for remanufacturing using AM. The application of this tool has been demonstrated with the help of a case study and a few examples. The limitations of the tool, case study and the challenges of implementing AM techniques are discussed. A comparison of remanufacturing with a laser additive machine and IIIP Monoprice printer is provided. Finally, the scope for future work has been discussed, which lays the direction for the expansion of this study and making the developed tool applicable to more diverse cases of remanufacturing.

References

Acharya, R., & Das, S. (2015). Additive manufacturing of IN100 superalloy through scanning laser epitaxy for turbine engine hot-section component repair: process development, modeling, microstructural characterization, and process control. Metallurgical and Materials Transactions A, 46(9), 3864-3875.

Adam, G. A., & Zimmer, D. (2015). On design for additive manufacturing: evaluating geometrical limitations. Rapid Prototyping Journal, 21(6), 662-670.

Ahn, D. G. (2011). Applications of laser-assisted metal rapid tooling process to manufacture of molding & forming tools—state of the art. International Journal of Precision Engineering and Manufacturing, 12(5), 925-938.

Alrbaey, K., Wimpenny, D., Tosi, R., Manning, W., & Moroz, A. (2014). On optimization of surface roughness of selective laser melted stainless steel parts: A statistical study. Journal of Materials Engineering and Performance, 23(6), 2139-2148.

Amezquita, T., Hammond, R., Salazar, M., & Bras, B. (1995). Characterizing the remanufacturability of engineering systems. In ASME Advances in Design Automation Conference. Vol. 82, pp. 271-278.

Atasu, A., Sarvary, M., & Van Wassenhove, L. N. (2008). Remanufacturing as a marketing strategy. Management Science, 54(10), 1731-1746.

Attar, H., Calin, M., Zhang, L. C., Scudino, S., & Eckert, J. (2014). Manufacture by selective laser melting and mechanical behavior of commercially pure titanium. Materials Science and Engineering: A, 593, 170-177.

Barry, K., Domb, E., & Slocum, M. S. (2010). TRIZ-what is TRIZ. The TRIZ Journal, 603-632.

Brent, A. C., & Steinhilper, R. (2004, September). Opportunities for remanufactured electronic products from developing countries: Hypotheses to characterize the perspectives of a global remanufacturing industry. In 2004 IEEE Africon. 7th African Conference in Africa (IEEE Cat. No. 04CH37590) Vol. 2, pp. 891-896.

Badrossamay, M., Yasa, E., Van Vaerenbergh, J., & Kruth, J. P. (2009). Improving productivity rate in SLM of commercial steel powders. Technical Paper-Society of Manufacturing Engineers, 1-13.

Bi, G., & Gasser, A. (2011). Restoration of nickel-base turbine blade knife-edges with controlled laser aided additive manufacturing. Physics Procedia, 12, 402-409.

Bras, B. (2014). Design for remanufacturing processes. Mechanical Engineers' Handbook, 1-28. (Ch 10)

Bogue, R. (2007). Design for disassembly: a critical twenty-first-century discipline. Assembly Automation, 27(4), 285-289.

Buican, G. R., Oancea, G., & Manolescu, A. (2014). Remanufacturing of damaged parts using selective laser melting technology. In Applied Mechanics and Materials Vol. 693, pp. 285-290. Trans Tech Publications.

Chang, Y., Bae, J. H., & Yi, H. C. (2013). Ultrasonic cleaning of used plastic parts for remanufacturing of multifunctional digital copier. International Journal of Precision Engineering and Manufacturing, 14(6), 951-956.

Champagne, V. K. (2008). The repair of magnesium rotorcraft components by cold spray. Journal of Failure Analysis and Prevention, 8(2), 164-175.

Chen, C., Wang, Y., Ou, H., He, Y., & Tang, X. (2014). A review on remanufacture of dies and molds. Journal of Cleaner Production, 64, 13-23.

Clare, A. T., Oyelola, O., Abioye, T. E., & Farayibi, P. K. (2013). Laser cladding of rail steel with Co–Cr. Surface Engineering, 29(10), 731-736.

Clijsters, S., Craeghs, T., Buls, S., Kempen, K., & Kruth, J. P. (2014). In situ quality control of the selective laser melting process using a high-speed, real-time melt pool monitoring system. The International Journal of Advanced Manufacturing Technology, 75(5-8), 1089-1101.

Coykendall, J., Cotteleer, M., Holdowsky, J., & Mahto, M. (2014). 3D opportunity in aerospace and defense: Additive manufacturing takes flight. A Deloitte Series on Additive Manufacturing, 1.

Crucibledesign.co.uk. (2019). Design guidelines for DMLS. https://www.crucibledesign.co.uk/images/uploaded/guides/bs7000-part-2-a-management-guide-download-original.pdf. Accessed on 2nd February 2019, 10AM CST.

Davis, J. R. (Ed.). (2004). Handbook of thermal spray technology. ASM International.

Ding, H. (2015). Remanufacturing by 3D Printing of Metals? A Great Potential But Big Challenge. 91-20.

Direct Energy Deposition. (2019) https://www.bintoa.com/directed-energy-deposition/ Accessed on 2019 Feb 3rd, 2:00 PM CST.

Errington, M., & Childe, S. J. (2013). A business process model of inspection in remanufacturing. Journal of Remanufacturing, 3(1), 7.

ETC/CDS. General Environmental Multilingual Thesaurus (GEMET 2000). https://www.eionet.europa.eu/gemet/en/concept/7015 Accessed on 5th April 2019 at 3:58 PM

Elmansy, R. (2016). https://www.designorate.com/practice-guide-to-solve-problems-with-triz/. Accessed on 2nd May 2019, 2:30 PM CST.

Everything you need to know about ABS plastic. (2019). https://www.creativemechanisms.com/blog/everything-you-need-to-know-about-abs-plastic Accessed on 25th April 2019 at 10:00 AM

Five challenges with additive manufacturing in the aviation industry. 2018. https://blog.satair.com/five-challenges-additive-manufacturing. Accessed on Oct 20th, 2019, 12:00 PM CST.

Frazier, W. E. (2014). Metal additive manufacturing: a review. Journal of Materials Engineering and Performance, 23(6), 1917-1928.

Galvanometer Mirror. (2019). https://www.britannica.com/technology/galvanometer Access on 11th April 2019 at 2:28 PM CST.

Gaytan, S.M., Murr, L.E., Medina, F., Martinez, E., Lopez, M.I., Wicker, R.B. (2009). Advanced metal powder-based manufacturing of complex components by electron beam melting. Materials Technology, 24(3), 180-190.

Gerard and Sahner (2017). Design for Metal Additive Manufacturing. https://indico.cern.ch/event/605200/contributions/2439513/attachments/1413131/2162939/Design_for_Metal_Additive_Manufacturing_R_GERARD.pdf. Accessed on 23rd April 2019, 7:00 AM CST.

Gibson, I., Rosen, D.W., Stucker, B. (2009). Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing. Springer, New York, NY.

Gibson, I., Rosen, D., & Stucker, B. (2015). Directed energy deposition processes. In Additive Manufacturing Technologies. Springer, New York, NY. 245-268.

Gong, H. (2013). Generation and detection of defects in metallic parts fabricated by selective laser melting and electron beam melting and their effects on mechanical properties.

Gonzalez, T. A. (1983). Remanufacturing technology. Doctoral dissertation, Massachusetts Institute of Technology.

Giutini, R., & Gaudette, K. (2003). Remanufacturing: The next great opportunity for boosting US productivity. Business Horizons, 46(6), 41-48.

Gray, C., & Charter, M. (2008). Remanufacturing and product design. International Journal of Product Development, 6(3-4), 375-392.

Grab Cad, Gas turbine blade. 2019. https://grabcad.com/library/gas-turbine-blade-4. Accessed on May 20th, 2019, 10:30 AM CST.

Hammond, R., Amezquita, T., & Bras, B. (1998). Issues in the automotive parts remanufacturing industry: a discussion of results from surveys performed among remanufacturers. Engineering Design and Automation, 4, 27-46.

Hatcher, G. D., Ijomah, W. L., & Windmill, J. F. (2013). Design for remanufacturing in China: a case study of electrical and electronic equipment. Journal of Remanufacturing, 3(1), 3.

Hu, Y., Madhava, M., & Renteria, F. (2005). U.S. Patent No. 6,905,728. Washington, DC: U.S. Patent and Trademark Office.

Heigel, J. C., Michaleris, P., & Reutzel, E. W. (2015). Thermo-mechanical model development and validation of directed energy deposition additive manufacturing of Ti–6Al–4V. Additive Manufacturing, 5, 9-19.

Hussain, T. (2013). Cold spraying of titanium: a review of bonding mechanisms, microstructure, and properties. In Key Engineering Materials (Vol. 533, pp. 53-90). Trans Tech Publications.

Ijomah, W. L., McMahon, C. A., Hammond, G. P., & Newman, S. T. (2007). Development of design for remanufacturing guidelines to support sustainable manufacturing. Robotics and Computer-Integrated Manufacturing, 23(6), 712-719.

Ijomah, W. L., McMahon, C. A., Hammond, G. P., & Newman, S. T. (2007a). Development of robust design-for-remanufacturing guidelines to further the aims of sustainable development. International Journal of Production Research, 45(18-19), 4513-4536.

Ilevbare, I. M., Probert, D., & Phaal, R. (2013). A review of TRIZ, and its benefits and challenges in practice. Technovation, 33(2-3), 30-37.

i-sim.org/Altshuller_Matrix.xls (2019). Accessed on 27th April 2019, 12 PM CST.

Jack Hipple. (2019). https://www.innovation-triz.com/triz/. Accessed on 20th April 2019, 10 AM CST.

Jiao, L., Chua, Z., Moon, S., Song, J., Bi, G., & Zheng, H. (2018). Femtosecond Laser Produced Hydrophobic Hierarchical Structures on Additive Manufacturing Parts. Nanomaterials, 8(8), 601.

Kelly and Dowie Rules
https://engineering.purdue.edu/LSM/courses/MEEM4685_5685/ERDM_Lecture19.pdf
Access on 31st March at 5:21PM CST.

Kerr, W., & Ryan, C. (2001). Eco-efficiency gains from remanufacturing: A case study of photocopier remanufacturing at Fuji Xerox Australia. Journal of cleaner production, 9(1), 75-81.

Kranz, J., Herzog, D., & Emmelmann, C. (2015). Design guidelines for laser additive manufacturing of lightweight structures in TiAl6V4. Journal of Laser Applications, 27(S1), S14001.

Kruth, J. P., Vandenbroucke, B., Van Vaerenbergh, J., & Mercelis, P. (2005). Benchmarking of different SLS/SLM processes as rapid manufacturing techniques. Laser, 1, 3D.

Lee, J. C., Kang, H. J., Chu, W. S., & Ahn, S. H. (2007). Repair of damaged mold surface by cold-spray method. CIRP Annals-Manufacturing Technology, 56(1), 577-580.

Leunda, J., Soriano, C., Sanz, C., & Navas, V. G. (2011). Laser cladding of vanadium-carbide tool steels for die repair. Physics Procedia, 12, 345-352.

Li, M., Liu, W., Short, T., Qing, X., Dong, Y., He, Y., & Zhang, H. C. (2015). Pre-treatment of remanufacturing cleaning by use of supercritical CO2 in comparison with thermal cleaning. Clean Technologies and Environmental Policy, 17(6), 1563-1572.

Linton, J. D. (2008). Assessing the economic rationality of remanufacturing products. Journal of Product Innovation Management, 25(3), 287-302.

Liu, Q., Janardhana, M., Hinton, B., Brandt, M., & Sharp, K. (2011). Laser cladding as a potential repair technology for damaged aircraft components. International Journal of Structural Integrity, 2(3), 314-331.

Liu, W., Zhang, B., Li, M. Z., Li, Y., & Zhang, H. C. (2013). Study on remanufacturing cleaning technology in mechanical equipment remanufacturing process. In Re-engineering Manufacturing for Sustainability. Springer, Singapore. 643-648.

Liu, W. W., Zhang, B., Li, Y. Z., He, Y. M., & Zhang, H. C. (2014). An environmentally friendly approach for contaminants removal using supercritical CO2 for remanufacturing industry. Applied Surface Science, 292, 142-148.

Liu, W. W., Li, M. Z., Short, T., Qing, X. C., He, Y. M., Li, Y. Z., & Zhang, H. C. (2015). Supercritical carbon dioxide cleaning of metal parts for remanufacturing industry. Journal of Cleaner Production, 93, 339-346.

Lourenço, J. M., Da Sun, S., Sharp, K., Luzin, V., Klein, A. N., Wang, C. H., & Brandt, M. (2016). Fatigue and fracture behavior of laser clad repair of AerMet® 100 ultra-high strength steel. International Journal of Fatigue, 85, 18-30.

Low, M. K., Lamvik, T., Walsh, K., & Myklebust, O. (2000). Product to service eco-innovation: the TRIZ model of creativity explored. In Proceedings of the 2000 IEEE International Symposium on Electronics and the Environment, 00CH37082, 209-214.

Lund, R. T., & Skeels, F. D. (1983). Guidelines for an original equipment manufacturer starting a remanufacturing operation (No. DOE/CS/40192-T2). Massachusetts Inst. of Tech., Cambridge (USA). Center for Policy Alternatives.

Mahamood, R. M., Akinlabi, E. T., & Owolabi, M. G. (2017). Laser metal deposition process for product remanufacturing. In Advanced Manufacturing Technologies. Springer, Cham. 267-291.

Matsumoto, M., Yang, S., Martinsen, K., & Kainuma, Y. (2016). Trends and research challenges in remanufacturing. International Journal of Precision Engineering and Manufacturing-Green Technology, 3(1), 129-142.

Matsumoto, M., & Umeda, Y. (2011). An analysis of remanufacturing practices in Japan. Journal of Remanufacturing, 1(1), 2.

Mazur, G. (1995). http://www.mazur.net/triz/. Accessed on 4th May 2019.

Mindtools.com (2019). TRIZ – A powerful methodology for creative problem-solving. https://www.mindtools.com/pages/article/newCT_92.htm. Accessed on 3rd May 2019, 10:00 AM CST.

Mobius – Defining a new era in tire manufacturing and recycling (2019). https://www.mobiusenviro.com/tire-technologies-pyrolysis-retreading/scrap-tyre-remanufacturing. Accessed on 5th October 12, 2019 at 12:00 PM CST.

Monoprice maker select plus review (2019). https://www.digitaltrends.com/3d-printer-reviews/monprice-maker-select-plus-review/ . Accessed on Aug 26th, 2019 at 2:20 PM CST.

Monoprice maker select 3D printer V2 (2019). https://www.monoprice.com/product?p_id=13860 . Accessed on 29th September 2019, 5:00 PM CST.

Mudge, R. P., & Wald, N. R. (2007). Laser engineered net shaping advances additive manufacturing and repair. Welding Journal-New York-, 86(1), 44.

Murr, L. E., Martinez, E., Amato, K. N., Gaytan, S. M., Hernandez, J., Ramirez, D. A., & Wicker, R. B. (2012). Fabrication of metal and alloy components by additive manufacturing: examples of 3D materials science. Journal of Materials Research and Technology, 1(1), 42-54.

Murr, L. E., Gaytan, S. M., Ramirez, D. A., Martinez, E., Hernandez, J., Amato, K. N., & Wicker, R. B. (2012 a). Metal fabrication by additive manufacturing using laser and electron beam melting technologies. Journal of Materials Science & Technology, 28(1), 1-14.

Murr, L. E., Gaytan, S. M., Medina, F., Martinez, E., Hernandez, D.H., Martinez, L., Lopez, M.I., Wicker, R.B., Collins, S. (2009). Effect of build parameters and build geometries on residual microstructures and mechanical properties of Ti-6Al-4V components built by electron beam melting (EBM). Solid Freeform Fabrication Symposium. 374-397.

Nasr, N. (2010). Reman for success. Industrial Engineer, 42(6), 26-27.

Nasr, N., & Thurston, M. (2006). Remanufacturing: A key enabler to sustainable product systems. Rochester Institute of Technology, 15-18.

Navrotsky, V., & CTO, P. (2014). 3D printing at Siemens power service.

Ortegon, K., Nies, L., & Sutherland, J. W. (2014). Remanufacturing. In CIRP Encyclopedia of Production Engineering. Springer, Berlin, Heidelberg. 1044-1047.

Payne, G., Ahmad, A., Fitzpatrick, S., Xirouchakis, P., Ion, W., & Wilson, M. (2016). Remanufacturing H13 steel molds and dies using laser metal deposition. Advances in Manufacturing Technology XXX; IOS Press: Amsterdam, The Netherlands, 93.

Paulic, M., Irgolic, T., Balic, J., Cus, F., Cupar, A., Brajlih, T., & Drstvensek, I. (2014). Reverse engineering of parts with optical scanning and additive manufacturing. Procedia Engineering, 69, 795-803.

Pinkerton, A. J., Wang, W., & Li, L. (2008). Component repair using laser direct metal deposition. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 222(7), 827-836.

Potter, L., Raje, S., Oftedal, J., Okudan Kremer, G., Bastias, A., Molenaar, K., Madson, K. and Franz, B. Developing a TRIZ-based Design for Flexibility Tool for Manufacturing Facilities. Proceedings of the IISE Annual Conference, Orlando, FL, May 17-22, 2019.

Rantanen, K., & Domb, E. (2007). Simplified TRIZ: New problem-solving applications for engineers and manufacturing professionals. Auerbach publications.

Raoelison, R. N., Verdy, C., & Liao, H. (2017). Cold gas dynamic spray additive manufacturing today: Deposit possibilities, technological solutions, and viable applications. Materials & Design, 133, 266-287.

Reinarz, B., Sehrt, J. T., Witt, G., Deiss, O., van Kampen, J., Münzer, J., & Ott, M. (2014). Optimization of media feed channels in Laser Beam Melting. In ASPE Spring Topical Meeting (pp. 13-18).

Ruan, J., Sparks, T. E., Fan, Z., Stroble, J. K., Panackal, A., & Liou, F. (2006). A review of layer-based manufacturing processes for metals. In Solid Freeform Fabrication Symposium (pp. 233-245). University of Texas Press, Austin.

Samperi, M. T. (2014). Development of design guidelines for metal additive manufacturing and process selection.

Seitz, M. A. (2007). A critical assessment of motives for product recovery: the case of engine remanufacturing. Journal of Cleaner Production, 15(11-12), 1147-1157.

Schnabel, T., Oettel, M., & Mueller, B. (2017). Design for additive manufacturing-guidelines and sase studies for metal applications. Fraunhofer Institute for Machine Tools and Forming Technology IWU, Report on Project, (141283).

Shamsaei, N., Yadollahi, A., Bian, L., & Thompson, S. M. (2015). An overview of Direct Laser Deposition for additive manufacturing; Part II: Mechanical behavior, process parameter optimization and control. Additive Manufacturing, 8, 12-35.

Shirwaiker, R. A., & Okudan, G. E. (2008). Triz and axiomatic design: a review of case-studies and a proposed synergistic use. Journal of Intelligent Manufacturing, 19(1), 33-47.

Shirwaiker, R. A., & Okudan, G. E. (2011). Contributions of TRIZ and axiomatic design to leanness in design: an investigation. Procedia Engineering, 9, 730-735.

Shu L.H., & Flowers W.C. (1999). Application of a design-for-remanufacture framework to the selection of product life-cycle fastening and joining methods, Robotics and Computer Integrated Manufacturing 15 (1999) pp 179-190.

Shu, L. H., & Flowers, W. C. (1998). Reliability modeling in design for remanufacture. Journal of Mechanical Design, 120(4), 620-627.

Srinivasan, R., & Kraslawski, A. (2006). Application of the TRIZ creativity enhancement approach to design of inherently safer chemical processes. Chemical Engineering and Processing: Process Intensification, 45(6), 507-514.

Steinhilper, R. (1998). Remanufacturing-The ultimate form of recycling. Fraunhofer IRB Verlag.

Sundin, E., & Lindahl, M. (2008, May). Rethinking product design for remanufacturing to facilitate integrated product service offerings. In Electronics and the Environment, 2008. ISEE 2008. IEEE International Symposium on (pp. 1-6).

Sundin, E. (2004). Product and process design for successful remanufacturing (Doctoral dissertation, Linköping University Electronic Press).

Sundin, E., & Bras, B. (2005). Making functional sales environmentally and economically beneficial through product remanufacturing. Journal of Cleaner Production, 13(9), 913-925.

Thijs, L., Verhaeghe, F., Craeghs, T., Van Humbeeck, J., & Kruth, J. P. (2010). A study of the microstructural evolution during selective laser melting of Ti–6Al–4V. Acta materialia, 58(9), 3303-3312.

Thompson, S. M., Bian, L., Shamsaei, N., & Yadollahi, A. (2015). An overview of Direct Laser Deposition for additive manufacturing; Part I: Transport phenomena, modeling, and diagnostics. Additive Manufacturing, 8, 36-62.

Triz40.com (2019). http://www.triz40.com/aff_Principles_TRIZ.php. Accessed on 22nd April, 2019 at 4:15PM CST.

Villafuerte, J. (Ed.). (2015). Modern cold spray: materials, process, and applications. Springer.

Walton, D., & Moztarzadeh, H. (2017). Design and development of an additive manufactured component by topology optimisation. Procedia CIRP, 60, 205-210.

Wang, J., Prakash, S., Joshi, Y., & Liou, F. (2002, August). Laser-aided part repair-a review. In Proceedings of the thirteenth annual solid freeform fabrication symposium, Austin, TX.

Wang, F. K., & Chen, K. S. (2010). Applying Lean Six Sigma and TRIZ methodology in banking services. Total Quality Management, 21(3), 301-315.

Wang, Y. L., Kong, Y. X., & Wu, B. H. (2012). Study on repair techniques of loader pin based on remanufacturing. In Applied Mechanics and Materials (Vol. 220, pp. 83-86). Trans Tech Publications.

Wei, S., Tang, O., & Sundin, E. (2015). Core (product) Acquisition Management for remanufacturing: a review. Journal of Remanufacturing, 5(1), 4.

Wilson, J. M., Piya, C., Shin, Y. C., Zhao, F., & Ramani, K. (2014). Remanufacturing of turbine blades by laser direct deposition with its energy and environmental impact analysis. Journal of Cleaner Production, 80, 170-178.

Xu, W., Brandt, M., Sun, S., Elambasseril, J., Liu, Q., Latham, K., & Qian, M. (2015). Additive manufacturing of strong and ductile Ti–6Al–4V by selective laser melting via in situ martensite decomposition. Acta Materialia, 85, 74-84.

Zhang, Y. L., Zhou, D., Jiang, P. S., & Zhang, H. C. (2011). The state-of-the-art surveys for application of metal magnetic memory testing in remanufacturing. In Advanced Materials Research (Vol. 301, pp. 366-372). Trans Tech Publications.

Zwolinski, P., Lopez-Ontiveros, M. A., & Brissaud, D. (2006). Integrated design of remanufacturable products based on product profiles. Journal of Cleaner Production, 14(15-16), 1333-1345.

Zhang, Y., Yang, Z., He, G., Qin, Y., & Zhang, H. C. (2015). Remanufacturing-oriented geometric modeling for the damaged region of components. Procedia CIRP, 29, 798-803.