Door Redesign on a Caterpillar Mid-Size Loader for Access to Oil Filter and Maintenance

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Door Redesign on a Caterpillar Mid-Size Loader
For Access to Oil Filter and Maintenance

A Major Qualifying Project
Submitted to the faculty of
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Date: March 2, 2014

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Abstract

Caterpillar Inc. is a worldwide leader in earth moving machinery. This project, in collaboration with Shanghai University, established a new access system for the oil filter on a Mid-Sized loader. This task was completed by first gathering design criteria from Caterpillar. Using the established design criteria and ISO specifications a design matrix was established and used to narrow designs down. The final designs were then optimized and sent to Caterpillar for review and feedback before choosing the final design.
Acknowledgements

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1 Introduction

In order to meet the needs of the working population it is necessary for companies to be flexible and adaptable to meet the needs of their customers. This means that companies should have the option of custom products and equipment to be competitive in their respective market. Custom products can be challenging and difficult for companies to produce, because they open up an entire new set of design requirements not previously sought out. Caterpillar Inc. is a perfect example of this; as one of the world’s leaders in construction equipment they are obligated to be innovative and reliable.

To remain competitive in the market, against competitors (Volvo and Komatsu for example) it is necessary that Caterpillar be open to custom projects. Because of this Caterpillar assigned the team to work on a custom project that had previously failed, to get the product on the market to stay ahead of their competition. The role of the team during the project was to work with one of the senior design engineers at Caterpillar, Danny, to come up with a new an inventive solution to their problem. To do this the team utilized the mechanical design process.

2 Background

This section reviews all of the background information that was needed before work on the project could begin. The section was crucial in the understanding of the project, company and the product it’s self as well as providing initial direction and focus.

2.1 Caterpillar Background

In 1925 Benjamin Holt and Daniel Best came together to form Caterpillar Tractor Co, in California, it stayed under this name until 1986 when it was rebranded as Caterpillar Inc. Today its headquarters are in Peoria, Illinois and it is the world-leading manufacturer of earthmoving, construction and mining equipment, as well as diesel and natural gas engines, turbines and diesel-electric locomotives. It is the umbrella organization for a vast array of smaller companies including market leaders; CAT, Olympian, FG Wilson, Perkins, E-Lect and MaK to name just a few. Since its’ beginning in 1925 Caterpillar has expanded to over 180 countries, with 500 different locations and selling over 300 products (About the Company, 2013).

2.2 Caterpillar in China

In 1975 Caterpillar was first introduced to China with the sale of 38 pipe layers, and then in 1978 it opened its first office in Beijing. Caterpillar has grown so large that in 1996 Caterpillar (China) Investment Co., Ltd. (CCI) was founded in Beijing to strengthen its business activities and investments in the country. There are currently 23 manufacturing facilities in China with three in Shanghai alone, manufacturing and selling 100s of different products (Caterpillar in China, 2013).
The team is specifically working with the Suzhou site, located 45 minutes outside Shanghai by high-speed train. The Suzhou site was started in 2008, and began manufacturing in 2009, they specialize in producing, mainly medium size wheel-loaders, as well motor graders. They market specifically to Asia Pacific, Russia, CIA, the Middle East and South America. It is important that the company has sites specifically marketing to different locations like this because the needs for different countries are different (Caterpillar: Suzhou, 2013). The team’s sponsor Brad gave a perfect example of this need, where he depicted the difference between a Chinese tractor and an American one. In America an operator is going to want a heat cabin to work in, because that is our culture, whereas in China it is not something they are going to care about because it is not something that they have ever had. However, just because different markets have different needs it is important to remember that a Caterpillar product is a Caterpillar product no matter where one is in the world, they are all build and held to the same company standard everywhere.

2.3 Loader Description

![Figure 1 Photo of a Wheel Loader taken at Caterpillar](image)

The team is working on a medium wheel loader used specifically in underground mining and steel mills. A wheel loader is a type of tractor that has a bucket on the front as shown in Figure 1 above, used to scoop up material on the ground and move it from one place to another. Medium wheel loaders are classified as those between 3 and 12 cubic yards in size, or 2.3 to 9.2 cubic meters (CAT, Equipment Wheel Loaders). The specific model in question is a custom product that is not currently in production due to the issue with the oil filter, because it is a custom project it is important to keep a few extra things in mind during the design process. When dealing with anything that goes underground it is crucial to keep safety as the first and foremost biggest concern. Another issue to keep in mind with machines used underground are noise, vibration and sealing from the elements.

Before starting the design process it was necessary to understand the constraints presented within the unit. In order to do this, the team went to visit Caterpillar to look at the loader and received a three-dimensional CAD (computer aided design) model of the loader as well. When receiving the model the team quickly noticed that some basic components were missing. The engineers had removed the current door and the hood from the model, because they thought that it would influence the team too much and they wanted a unique out of the box design. From the model the team was able to gather basic
information such as material selection, space constraints, size of the oil filter and location of other parts in reference to our design. The size of the oil filter was the second most important piece of information gathered, as it needs to be directly proportional to the size of the door for proper maintenance.

Using the drawings and models received from Caterpillar, the team gathered crucial design information to be used in the brainstorming and design processes. The first piece of information needed was the exact space limitation presented between the egress ladder and the hood, as this was the current problem. One additional thing that had to be kept in mind here was that due to the nature of the frame, the space available was not constant but varied slightly. The space limitations are described in Figure 2 below.

![Figure 2 Schematic of the space constraint between ladder and the hood](image)

<table>
<thead>
<tr>
<th>D₁</th>
<th>D₂</th>
<th>D₃</th>
<th>D₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>273.05mm</td>
<td>221.9mm</td>
<td>27.9mm</td>
<td>233.36mm</td>
</tr>
</tbody>
</table>

When:

- D₁ is the distance between the hood and the ladder
- D₂ is the x-axis distance between the right constraint of the doorframe and the closest railing
- D₃ is the gap between the right constraint of the doorframe and the hood
- D₄ is the distance between the hood and the rail
It was also important to understand exactly how large the oil filter is and its location in relation to the hood and the turbo engine in order to make sure that door was large enough to perform routine service. The oil filter is 390 millimeters long and 135.8 millimeters in diameter, both extremely crucial to making the door the proper size (Figure 3).

![Figure 3 Exact size and shape of the oil filter used in the loader](image)

Since the oil filter will be removed it is imperative to make sure the door is larger than the above filter so the operator was adequate room to work. The oil filter's location is also important, as it will dictate both the length of the new hood and door. The oil filter is located 627 milliliters from the left edge of the hood, shown in Figure 4 below.
Figure 4 Exact location of the oil filter in model

The turbocharger is the yellow block located 325 millimeters above the oil filter, as shown above, and must be completely out of the way from the operator during service. The turbocharger runs at extremely hot temperatures and would pose an unsafe working condition if the operator was able to come into contact with it during service. Turbochargers are commonly used in racecars, high performance sports cars and large diesel engines, as they significantly increase the engines horsepower without drastically increasing its weight.

Turbochargers compress the air flowing through the engine, allowing the engine to squeeze more air into each cylinder, which means that more fuel can be added. More fuel means more power, and because the turbocharger is not significantly heavy they overall increase the power-to-weight ratio of the engine, which makes it ideal for large construction equipment (Nice, 2000). The turbocharger cannot work alone to achieve this boost in performance. The turbocharger is connected to the engines exhaust pipe and using the exhaust flow it spines a turbine spinning the air pump. Common turbines in turbochargers run at speeds up to 150,000 rotations per minute, because of this and the fact that it is connected to the engines exhaust is the reason that it operates at extremely high temperatures. Along with the danger that can come from the high temperature is another issue cause by the turbine. The turbine works like a vacuum pulling air from the outside as well as other small debris. This debris then enters the inner chamber of the loader, and can cause major issues if it is allowed to build up decreasing the life expediency of the product. Now that the basics of the model are understood more detailed information can be sought out and the design process can begin.

2.4 Mechanical Design Process

When developing a new product or customizing an already existing one it is necessary to do it in a systematic manner for optimal results; this is known as the mechanical design
process. The design process can be broken down into six steps; 1) recognition of need, 2) definition of problem, 3) synthesis, 4) analysis 5) optimization and 6) evaluation (Childs, 2004).

Recognition of need is critical because without it there would not be a project. This is the step in which the company or individual recognizes a need or potential market for a new product, design or process. After the project is initialized, the problem must be defined. During this step it is necessary that a thorough list of specifications be laid such as dimensions, limitations, inputs and outputs, and characteristics, this will allow for a much easier brainstorming process and will save countless hours of time. Once, the problem is defined the “design” process can begin, known as the synthesis stage.

Synthesis is when ideas and concepts are combined and formed, offering potential ideas or answers to the above problem. In many cases this stage can be seen as brainstorming. The last three steps, analysis, optimization and evaluation are when the ideas and design come together.

Analysis directly follows the synthesis stage, it utilizes engineering science to examine the design to give quantitative information and point out any potential problems. Optimization and evaluation are when the design criteria are redefined to achieve the best compromise for the problem, and to identify if will satisfy the original requirements set out (Norton, 1996).

2.5 Recognition of Need

The purpose of this project was to come up with a solution to the following problem provided to the team by the company: “the door [on the wheel-loader] cannot open freely due to constraint of space between egress ladder and hood. Access to the oil filter periodically is mandatory, and egress ladder is mandatory, too.” The company provided little information to the team other than that the current door could not open because of a space constraint provided by the egress ladder, and side of the hood. Upon further research and speaking with the engineers the team was able to come up with a narrower scope, an objective. The objective of the project is to allow access to the oil filter, by allowing the door to freely open. The objective was then broken down in visually to get a better understanding of how this goal could be met Figure 5.
The more specific goal is to create a safe, and out of the box door design or modification that will allow the door to freely open so proper maintenance of the oil filter can occur. The design needs to most importantly be safe and must not put the operator in harm’s way of any sorts. The design should abide by the following ISO specifications; ISO2867, ISO3457, and ISO20474. It should be cost effective, not have too many special parts, limit sound transmission, seal properly and limit vibration. Other than the above listed requirements the company was open to any design as long as it mechanically, and structurally sound as well as safe.

2.6 Definition of Problem

The team was tasked to come up with a solution to an error in an initial design of the service door on Caterpillar’s mid-size loader. The problem is that currently there is no access to the oil filter for maintenance, because the door, which houses the oil filter, cannot freely open. This is due to the space constraint between the egress ladder and the hood of the tractor. Both the egress ladder and the hood are necessary components of the tractor. The ladder is the only means of travel into and out of the cockpit, and the door is required to provide shelter and ease of access.

2.7 Problem Justification

In order to keep the loader running smoothly, proper maintenance needs to be administered. Part of this maintenance requires changing the oil filter. The oil filter works in conjunction with the oil pump to keep the engine running smoothly. As the oil pump circulates the oil it must pass through the filter before entering into the engine to remove any particles that may be residing in the oil as to not clog up the engine (Cohen, 2012). If proper maintenance of the oil filter is not taken care of it can be destructive to the engine and overall life span of the product. Maintenance of the oil-filter is required every 500 hours, and should be able to be performed in a simply and timely manner (Caterpillar Sponsor).
3 Design Consideration and Priorities

When coming up with initial designs it is necessary to understand the limitations in the current design, to get a better understanding of what does and does not works. It is also crucial that the design meets both customer and company specifications because they are the ones investing in the product. Lastly, it is necessary that all federal and internal guidelines be met for the product.

3.1 Understanding Inadequacies in Current Design

The current door and hood combination on Caterpillar’s loader does not allow for service of the oil filter. The door cannot be opened because it is too large to operate within the space provided between the hood and egress ladder. The team was not given exact specification, dimensions or locations of the current door or hood. The model received had all the inner working, the door and the hood taken out. The sponsors did this as to not influence the teams design process in any way, essentially giving a blank canvas in which to work with.

3.2 Internal Organization of Standardization Specifications for Earth Moving Machinery

ISO standards are a list of internationally accepted specifications published by the International Organization of Standardization. ISO standards ensure the safety and quality of the product, process, and design are of highest quality. In the designing process, Caterpillar required that all of the designs comply with three sets of ISO standards: ISO-2867, ISO-3475, and ISO-20474.

3.2.1 ISO-2867: Earth Moving Machinery-Access System

ISO-2867 deals with the access systems, steps, ladders, walkways, platform, grabs rail/handrails, grab handles, guardrails and enclosure entrance and exits, of the earth-moving machinery. Access systems are defined as “system provided on a machine for entrance to and exit from an operator, inspection or routine maintenance platform from and to the ground.” This includes ladders, rails, and entrance and exit openings (door.). It outlines the specifications, which the designs shall comply with in order for the operator to perform routine maintenance.

Section 4 of ISO-2867 outlines the following requirements that must be present in the final design:

- 4.1.1 “Correct use of the access system for hand and foot placement shall be self-evident without special training.”
- 4.1.2”Protruding devices of the access system that could create a hazard by catching or holding body appendages or wearing apparel shall be minimized.”
- 4.1.4 “User contact with potential hazards such as extreme differences in heat or cold, electrical hazards, moving parts and sharp corners shall be minimized.”
3.2.2 ISO-3475: Earth Moving Machinery - Guards Definitions and Requirement

ISO-3475 focuses on the guard structure for protecting personnel against mechanical, fluid or thermal hazards associated with operation and maintenance of the earth-moving machinery. A guard is defined as any “protective device, alone or combined with other parts of the machine, designed and fitted to minimize the possibility of contact with a potentially hazardous machine component” Therefore, this includes the door designs.

The following requirements laid out in Section 4 General Requirements are applicable to the designs:

- "4.2 Guards shall be attached to the machine with common fasteners or other effective means. Access doors and guards which need to be opened for routine or daily maintenance, inspection or cleaning.
  - Shall be easy to open and close,
  - Shall remain attached by a hinge, tether, or other suitable means,
  - Shall include means to keep them closed and, when required, open."

- “4.3 Guards which need to be opened for maintenance shall be free of sharp edges and corners and projections, and have sufficient strength under expected climatic and operational conditions for their intended use.”

- “4.4 Each guard (excluding hose guards) shall be sufficiently rigid to avoid deflection into the hazardous component and to avoid detrimental permanent deformation under the following loads applied by means of a 125 mm diameter disc:
  A) If a person can touch the guard — 250 N applied at possible points of contact;
  B) If a person can fall or lean against the guard — 500 N applied at possible points of contact;
  C) If the guard also serves as a step or platform of the access system — 2000 N applied at any location on the surface (see ISO 2867).

3.2.3 ISO-20747- Earth Moving Machinery-Safety

ISO 20474 is a complied series of standards to be utilized for different type of earth-moving machinery, and ISO-20474-3 is the specific one to be used for loaders. However, after reviewing ISO-20474-3, it was found that the requirements are not related to door or ladder designs; therefore, it is not applicable to the final designs.

3.3 Caterpillar and Customer Specifications

After reviewing the current design and ISO specifications the team spoke with the engineers at Caterpillar regarding any further company or customer specifications. Brad the main contact at Caterpillar did not want to influence the team in any way so he said
that he was looking for the safest design that would be of the greatest value to the consumer. Brad was not looking for anything specific but told the team that the following must be kept in mind during the design process in order to make the design safe and profitable:

1. During service the operator cannot-
   a. Come into contact with the turbocharger, as it is extremely hot.
   b. Be near anything that is hot or sharp be on the door, mechanism or preexisting on the loader.
   c. Bend over or reach too far to perform service.

2. The door should not
   a. Have any easy pinch points
   b. Easily close from a gust of wind
   c. Block the walkway when the machine is under normal use

3. The door must close fully, it does not need to lock because it will not be used in public places only underground.

4. The door should seal well. The door should not allow for debris or fluid to pass through.

5. The door and its components should not produce excess levels of vibration.

6. The door should limit the amount of sound transmission produced.

7. The door should be corrosion resistant, meaning that it prepared for paint. If the team does not change the material form that what is already used this should not be a problem.

8. The door and its components should be easy to use and not require special training.

### 3.4 Design Goals

After reviewing both ISO standards: 2867, 3475, 20474 and Caterpillar and customer specifications they can be summarized into the following 8 requirements:

1. No instruction should be needed to use the door.
2. When using the door, the operator must not come into contact with the Turbocharger because it is extremely hot.

3. When using the door, the operator should not come into contact with any potential dangers such as sharp edges.

4. The door needs to remain attached to the loader.

5. The door must fully close.

6. The door needs to be able to withstand a force of 250 N at any point.

7. The door needs to seal properly, and limit sound transmission and vibration.

8. The door should be corrosion resistant.

4 Methodology

The goal of this project was to develop a creative and innovative solution that will allow operators easy and convenient access to the oil filter on the Mid-Size Loader. The following goals were developed in order to achieve this project goal:

1. Understand the shortcomings in the current design, hindering access to the oil filter
2. Develop preliminary designs that meet the needs of Caterpillar and the customer
3. Determine the most adequate design
4. Validate most optimal design based on Caterpillar feedback

The project was completed during the fall semester of 2013 and was broken into two parts: 1) Pre-Qualifying Project (A-term 2013), and 2) Major Qualifying Project completed in Shanghai (B-term 2013).

4.1 Pre-Qualifying Project Plan

The Pre-Qualifying Project (PQP) was completed during A-term 2013. During this time the team revived the project statement from Caterpillar and their teammates at Shanghai University. The goal of this period was to prepare for the MQP period during B-term. To achieve this goal the following sub-goals were developed:

1. Research company and specific loader model
2. Set up a form of communication with Shanghai University students and Caterpillar Sponsors
3. Understand designs shortcomings, and define the problem
4. Create a plan for achieving design goals
5. Set up a MQP plan for B-Term

To achieve these goals the team created a “PQP plan” which is outlined below.
During PQP, the team was given the problem from Caterpillar. During week one and two research was conducted on company background and the problem statement was defined. Week three communication was set up with Shanghai University students and bi-weekly meetings were scheduled via QQ an online communication tool similar to Skype. Once all students had an understanding of the project and the objectives were defined the team reached out to their Sponsors at Caterpillar for more information and clarification on the project. After that, we reached out to the sponsor to obtain more information about the project. After getting a reply from Caterpillar, brainstorming was done on possible approaches to solve the problem. In addition, research into the design process and evaluation methods such as the design matrix was completed. Finally an action plan for the MQP project was setup.

4.2 Major Qualifying Project Plan

During B-term 2013 the team traveled to Shanghai to complete the Major Qualifying Project. During this time the main focus was working with SHU students to develop and present multiple designs to Caterpillar for review and final selection.
While working on the MQP, the team followed the action plan (Figure 7) set up during PQP. During the first week in Shanghai the team visited Caterpillar to present their understanding of the project, their plans and to gather information on the Loader and manufacturing process. Throughout the next two weeks the team preliminary designs were developed. After narrowing down the preliminary designs work on the CAD models was started (beginning of the third week), and a Gantt chart was created in order to specify more detailed tasks and determined the time frame. Figure 8 shows all tasks involved with the respected time frame.

![Gantt Chart](chart.png)

**Figure 8 Weekly breakdown of MQP period with goals to be accomplished**

After the CAD models were completed the team evaluated each designs, and present them to Caterpillar for feedback review and final design selection. During the last two
weeks of MQP the final design was optimized, and the final presentation with design advantages and disadvantages for Caterpillar was prepared.

5 Preliminary Designs

After brainstorming, reviewing ISO requirements, space constraints and feedback from the engineers at Caterpillar the team decided the most logical idea would be to modify the door and came up with four design ideas; 1) The four bar, 2) Double-slider, 3) Zigzag or bi-fold and 4) Two-Door. The four final ideas were drawn up in CAD, and then evaluated based on the design matrix, ISO requirement, and mechanical performance. The designs and analysis was then presented to Caterpillar illustrating the strengths and weaknesses for feedback and review.

The four designs can be broken down into two categories; 1) Center-door, and 2) Full-door. Both the two-door and zigzag door will be center doors whereas the four bar and the double-slider will be full-door ideas. The current door design utilized by Caterpillar is a full-door, the door was fixed to the right side of the hood and locked into the left piece of the hood. The oil-filter was located close to the locking side of the door leaving empty space to the right, which the team sought to minimize, as the door was too large to open this way. It was made clear that a center door, if done properly, would be able to eliminate a lot of unnecessary material from each side of the door therefore reducing its width and ideally allowing it to open.

5.1 Center Door Design

The center door concept sought to place the door in the middle of the hood directly over the oil filter, Figure 9.
Since the hood was removed from all drawings and models received from Caterpillar the exact current location of the door was unknown. With both center doors the design of the hood was drastically changed to reflect the new concept. The new hood design was a three-piece design consisting of a top part, right part and left part. The top part of the hood was necessary to cover the turbo engine, which runs at extremely high temperatures and must not come into any form of contact with the operator. The three pieces of the hood were mated together with an opening on the bottom with a hole in the middle for the door. The basic design of the hood is the same for both doors, Figure 10, however the measurements very slightly.

Figure 10 Hood design as drawn in SolidWorks

5.1.1 Zigzag Door Design

The zigzag door or bi-fold door is a simple concept that can be seen in many places ranging from closet doors to sliding hospital doors as shown below in Figure 11.
Figure 11 Example of a Zigzag door on a back patio (http://www.slideandfold.co.uk/four-pane-bifold-plus-made-to-measure-)

It is a very simple design with one door broken into two halves, one fixed joint and one hinge. The door will unlock on one end and freely open. Using the hinge in the middle the door will have the potential to fold in half, if needed, bypassing the ladder, as shown in the schematic below. The hinge in between the panels in moveable depending on the clearance needed.

Figure 12 Schematic of the Zigzag door

5.1.2 Two-Door Design

The two-door design is commonly seen on 12 passengers van and is where the team came up with the idea, Figure 13.
Figure 13 The top figure shows the closed "two-door" design used on a commercial 12-passenger van and the bottom picture is a illustration of the doors when they are open (http://www.ford.com/commercial-trucks/eseries-cargo-van/).

This is a very basic design that utilizes two fixed joints on both ends; with two separate doors interlocking in the middle. The two doors will have varying shapes due to the upward slop of the stairs. The door closest to the top will have an angled corner mimicking the stair shape. The door on the bottom will be a simple rectangle. One advantage of this design is that when using two doors, you can control the width of both doors, ideally bypassing the space constraint due to the stairs position. A basic schematic of the design is detailed below.

Figure 14 Schematic of the two door design
5.2 Full Door Concept

The full door concept uses Caterpillar’s original hood design making modifications to the size, and only has one door this time. Instead of having a three-section hood like the center door design this hood is only one piece, located on the left hand side of the loader. The size of the new hood needed to be larger than the original hood, so the size of the door could be decreased. The hood can be at most 627 millimeters in length as the oil filter is located 627 millimeters away from the left edge of the hood, as shown below, it however most be smaller than that in order for proper service to take place.

![Figure 15 Location of the oil filter in regards to the hood](image)

The hood will mimic the left side of the frame and be welded into place; the actual size of the hood will vary slightly for the two designs. For both designs the door will be located on the right side. The door be fixed into the right hand edge, and will open from the left where it is locked into place.

5.2.1 Four Bar Design

A four bar linkage is one of the most common types of linkages used in machinery and mechanical equipment in which there are three different types: plane, spherical and skew. For this design a plane four bar linkage will be used. A plane four bar linkage is composed for four links connected by pins forming a closed loop (Freudenstein, 2012). Depending on the lengths of the links, and the degrees of freedom the linkage will move in varying paths of different lengths and shapes. The type of motion is determined by Grashof’s inequality, which states that:

\[ L + S < M_1 + M_2 \]

Where:
- \( L \) is the length of the longest link
S is the length of the shortest link
M₁ is the length of one of two reaming links
M₂ is the length of the last link

If the inequality is satisfied there are three possible mechanisms depending on where S is connected to the ground. If S is fixed to the ground on both the bottom and the top a double crank results, if it is fixed on only one end a Crank-Rocker results and if it is not fixed at all a double rocker will results:

![Crank-Rocker](image1)
![Crank-Crank](image2)
![Rocker-Rocker](image3)

Figure 16 Grashof's Law examples

However if the inequality is not met a double rocker mechanism will results as well (Norton, 1996). Once, the type of mechanism is determined, its path will be indicated by the actual lengths of each link with countless numbers of paths available. The four bar mechanism used for the door is a basic crank-rocker with only one fixed point.

The design utilizes one door, and one fixed joint with a locking mechanism at the opposite end and a joint in the middle. The door will be the free rod of the four bar mechanism and will open outward. When the door is opened it will cause a bend in the joint allowing movement and access to the oil filter. By placing the joint in the middle it allows the door to open within the space constraint.

![Figure 17 Schematic of four bar mechanism](image4)
5.2.2 Double Slider-Crank Design

![Diagram of double slider mechanism](image)

Figure 18 Schematic of the double-slider mechanism with door

This is the most complicated and most expensive design. It is composed of a crank and two sliders to from another type four bar mechanism, a double-slider crank. A double-slider crank is classified as a four bar linkage with two parallel joints, and two sliding joints (Reuleaux, 1876).

The above blue arrow is where the door will be attached to the hood, the door is the entire section from slider 1 to slider 2, and it will open outward based on the path of motion produced from the desired link lengths.

This design gives a lot of freedom with the path the door will ultimately take to open. Motion analysis in SolidWorks was used to determine if a mechanism could be developed that fits the space constraint, and how the altering lengths of the linkages will affect the doors path. This design has to utilize many customize parts that Caterpillar cannot source from their current inventory.

5.3 Sourcing of Parts

When creating the designs, the team tried to use as many standard parts as possible to minimized sourcing. Doing so will also minimize the design and manufacturing cost.

Standard locks and hinges were used from Caterpillar list of current parts. The parts used are shown below, and a summary of the parts is located in Table 1.
5.3.1 Door Hinges

Figure 19 Hinges sourced from Caterpillar’s main supplier; left hinge is denoted as part Hinge#1, right hinge is denoted as part Hinge#2

5.3.2 Locks

Figure 20 Locks sourced from Caterpillar’s main supplier; left lock is denoted as part Lock#1, right hinge is denoted as part Lock#2

Table 1 Standard parts used in all designs

<table>
<thead>
<tr>
<th>Design</th>
<th>Part</th>
<th>Number Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zigzag</td>
<td>Lock#1 (Lock)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Hinge#1 (Hinge)</td>
<td>4</td>
</tr>
<tr>
<td>Two Door</td>
<td>Lock#1 (Lock)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Hinge#2 (Hinge)</td>
<td>4</td>
</tr>
<tr>
<td>Four Door</td>
<td>Lock#2 (Lock)</td>
<td>2</td>
</tr>
<tr>
<td>Double Slider-Crank</td>
<td>Lock#2 (Lock)</td>
<td>1</td>
</tr>
</tbody>
</table>
5.3.3 Custom Parts

The Two Door Design and the Zigzag Door Design only require the standard parts. However for the four bar Design and Double Slider-Crank Design, custom parts are needed for the mechanism to work.

5.3.3.1 Four Bar Custom Parts

The four bar mechanism will need four special parts to be manufactured for the final design. These four parts will be manufactured by Caterpillar from steel blocks cut to the desired shape and size. There are several ways including laser cutting and molding that can be used to manufacture these parts. Caterpillar will base this on their specialties. Below are the custom parts needed for the design.

![Figure 21 Hinge with no hole](image1)

![Figure 22 Hinge with hole](image2)
5.3.3.2 Double Slider-Crank Custom Parts

The Double Slider-Crank with also utilize many custom parts. The entire slider will need to be custom made including the pins, wheels, bearings, bearing caps and wheel chassis. The crank and guides will also need to be custom made by Caterpillar. Three methods will be used for the manufacturing process of these parts, casting, molding and laser cutting. The wheel chassis, slider limiter, guide the outer and inner wheel, the 96 rolling pins, top pin and slider-crank hinge will be either laser cut from steel or molded depending on Caterpillar’s preference. Casting will be needed to make the following parts: outer wheels, inner wheels, rolling pins, top pin and slider-crank hinge.
6 Design Selection

The four preliminary designs will be analyzed based on the previously outlined goals, overall cost and ergonomics. In order to do this the team created a design matrix based off of Caterpillar’s Pugh Matrices, reviewed the manufacturing and materials cost and study the ergonomic required for each design.

6.1 Design Matrix

When coming up with a final design there must be a measurable way to distinguish one design from another. In conjunction with the sponsors from Caterpillar the team came up with a simple design matrix based off of Caterpillar’s Pugh Matrices. The basics of a Pugh Matrix are simple each design parameter (i.e cost, safety) is giving a priority ranking based on how important it is to the overall design of 1, 3 or 9. The numbers 1, 3, and 9 were given to the team by Caterpillar to use, as they are easy to distinguish between, unlike other matrices where 1-10 is utilized. Once the priority ranking is complete each design is given a design ranking for each parameter of 1, 3 or 9. Lastly, the priority ranking and design ranking are multiple and summed for each design depicting an overall winner. Other advantages and disadvantages were also taken into consideration when choosing the final design in conjunction with the design matrix. An example of a design matrix can be seen below.

Figure 25 Exploded view of the slider with custom parts
Table 2 Example of completed Design Matrix

<table>
<thead>
<tr>
<th></th>
<th>Design 1</th>
<th>Design 2</th>
<th>Design 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reliability</strong></td>
<td>9</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td><strong>Ease of Use</strong></td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td><strong>Performance</strong></td>
<td>3</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>1</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td><strong>SUM</strong></td>
<td>42</td>
<td>72</td>
<td>36</td>
</tr>
</tbody>
</table>

6.2 Design Matrix Parameters

The parameters in the design matrix are general topics that encompass the design specifications into a condense easy to read table. As stated above the parameters are ranked on how important they are to the overall design. The priority ranking of each design was based on feedback from the team’s sponsor, outline below, taken from an email from Brad.

“Generally, in our [Caterpillar’s] Pugh matrices, I [Brad] would do something like you are thinking about. Each factor would get a priority ranking. Then I would rank the designs as a 1, 3, or 9. Then you multiply all the priority rankings by the 1, 3, or 9 and sum.

For you, I would put the order as follows (I also propose a priority ranking):

Priority Ranking
9 Reliability (most important almost all the time)
3 Ease of Use (including weight) (important but not a 9 since it is only used once every 500 hours for filter change, it is not daily)
1 Cost (least important since all of them will be affordable and this is an attachment that people can choose or not)
3 Performance (important but not top)”

6.2.1 Reliability

Reliability is “the extent to which an experiment, test, or measuring procedure yields the same results on repeated trials” (“Reliability”) and is one of the most important parts of the overall design and is therefore giving a priority ranking of a 9. Reliability is how well
one can depend on the design to work every time without fail. This encompasses many different design specifications in order to ensure that it works properly every time.

Reliability was measured both objectively by reviewing the design’s pros and cons and by doing mechanical analysis. When testing for reliability, it is important to keep the customer in mind, their needs and wants must be met. For this door, that means it must meet safety specifications, and previously outlined design specifications. All designs were tested to make sure the hood, the hinges and special parts, in some designs, could support the door and it component’s weight. It was also important to make sure that the design was safe, both during normal operation and maintenance.

6.2.2 Ease of Use

Ease of use is important when the operator is using the product. Since the oil filter only needs service every 500 hours (Caterpillar, 2013), the door will only be opened every 500 or so hours. Due to this ease of use was only given a priority ranking of 3. The two main components of ease of use are force and time, both of which will be important when maintenance needs to take place. Among all four designs, time should be fairly consistent, since opening and closing the door will not vary greatly from design to design. Ease of use is measured using ergonomic analysis method called EAWS. This method is explained and shown in section 7.1.1 “Ergonomic Analysis”.

6.2.3 Performance

For the door, performance is fairly simple and it is not a major overall design factor so it was only given a ranking of 3. When describing performance there is not clear cut definition used across the board for all companies and projects. To understand performance of design one must first understand what design is according to O’Donnell and Duffy “Design may be seen as a process of goal-directed reasoning where there are as many possible (good) solutions and although the process can be supported methodologically, it cannot be logically guaranteed.” Second, it is crucial to understand the design overall goals. Once the two of these were laid out the team began to evaluate the overall performance.

The first step in measuring the performance was to understand what the design goals, previously established in section 3.4, were. These goals were kept separate from the ISO specifications. Even though ISO specifications are designs goals that must be met or the design will fail so the team decided it would be best to keep them as a separate entity. A recap of the designs goals, that will be used to measure performance:

1. The door must easily open without interfering with any other parts of the machine.

2. The design must limit against vibration, as not to produce access noise when in operation, or wear caused from the constant rubbing motion of the material.
3. The door must seal to protect the oil filter from the environment. The door must be corrosion resistant, meaning that it needs to be designed for paint.

4. The design is corrosion resistant

As previously described each design criteria received an overall design ranking of 1, 3 or 9. The performance of the design received the design ranking based on the previously listed goals, in section 6.2. In order to decide the design ranking it was necessary to come up with a point system for the goals that corresponded to a 1, 3 or 9.

Each goal will be awarded goal points depending on how well the design meets the criteria. To factor in priority of the goals a factor of two was multiplied to the goal points for goals 2 and 3. Goal 1 was not considered to be of as high importance of because a door can easily open without interfering with other parts of the loader, but still have many issues such as locking, sealing, vibration etc. Goal 4 was also not multiple by two because the team did not change any of the materials that Caterpillar is currently using. Therefore all designs were considered to be corrosion resistant such as the original material is. Goal points will be awarded as follow:

Goals 1 and 4

0 Points- Does not meet design criteria/goal
1 Point- Meets design criteria/goal

Goals 2 and 3

0 Points- Does not meet design criteria/goal
1 Point- Meets design criteria/goal
2 Points- Exceeds design criteria/goal

Since there are four design goals, two receiving 1 possible point and two receiving 2 possible points there are a total of 6 points that can be awarded to any one design. So the following design points will correspond to the design ranking as listed in Table 3:

<table>
<thead>
<tr>
<th>Design Ranking</th>
<th>Goal Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-2</td>
</tr>
<tr>
<td>3</td>
<td>3-4</td>
</tr>
<tr>
<td>9</td>
<td>5-6</td>
</tr>
</tbody>
</table>

6.2.4 Cost
In any design it is important to factor in cost because customers want to get the best value for the lowest price while the producer want to minimize the manufacturing cost. Since the loader we are working with is a custom design, our door design is considered a premium product; therefore, Cost is given a priority ranking of 1. There will be four factors considered when calculating the final cost; laser cutting, material cost, standard parts cost, and custom parts cost. The cost analysis is explained and shown in section 7.1.3 “Cost Analysis”.

7 Analysis of Designs

Analysis is defined as the “careful study of something to learn about its parts, what they do and how they are related to each other (“Analysis”).” During this stage the designs are validated, they can either be proven a success or failure. The analysis stage will vary from design to design depending on what the overall goals are. Since the team is composed of both Mechanical and Industrial Engineers it was important to look at both aspect of the design to fulfill the MQP requirements for all members.

7.1.1 Mechanical Analysis

Most of the mechanical analysis that was completed falls within various categories of the design matrix, and was conducted using SolidWorks. Due to time constraints and the nature of the project a more thorough mechanical analysis was completed only on the top two designs, the four-bar and Double Slider-Crank as the other two were previously eliminated. After speaking with Caterpillar and choosing the final design (double-slider) an additional analysis was completed.

In order to make sure the design was going to be safe and reliable Finite Element Analysis and Von Mises analysis were performed in Solidworks. The results of this can be seen in section 8 Final Design. Finite Element Analysis uses a series of numerical methods to provide answers to problems that would be extremely hard to solve. FEA uses a system of points called nodes at various locations placed on the system to join the different elements together making a mesh. This mesh is programed with material and structural properties so that it reacts properly to the various loading conditions during testing. At this various testing can be done on the object in one of two ways 2-D modeling or 3-D modeling, where 3-D modeling produces more accurate results (Introduction to Finite Element Analysis)

Finite element analysis is used to ensure the quality, performance and safety of the design. In Solidworks the displacement formulation of the finite element method is used to calculate the component displacement, strains and stress under the internal and external loads, loads can be imported from thermal, flow and motion Simulation studies (Finite Element Analysis).

Along with FEA, the vin Mises stress will be calculated for the designs. Von Mises stress, is the stress at which yielding is predicted to occur in ductile material. The stress ($\sigma'$) is calculated using the following equation:

$$\sigma' = \frac{1}{\sqrt{2}}\left[\left(\sigma_1 - \sigma_2\right)^2 + \sigma_2 - \sigma_3)^2 + \sigma_3 - \sigma_4\right]^{1/2}$$
based on the principal axes (Jong & Springer 2009) This means that when the distortion energy density reaches a critical value for the material it will yield. This is very important for the designs because it is crucial that the door and hood does not crack under pressure. Since it is being used in underground mining and steel mills there will be at times additional stress placed on it.

7.1.2 Ergonomic Analysis

For safety purposes, in the designing process, it is important to take into consideration of how the operator will interact with the design. In the designs, the team focused on the mechanisms and postures the operator will use to open the door.

7.1.2.1 Posture Required for Maintenance

![Engineer Danny demonstrating the maintenance posture for the Zigzag and Two-Door designs (Posture A)](image)

The Zigzag door and Two Door require the operator to sit in the position shown in Figure 26 to open the maintenance door. This will be called posture “Posture A” for future reference.
On the other hand, the Four Bar and the Double Slider-Crank designs require the operation to sit in the position shown in Figure 27. This will be called posture “Posture B” for future reference.

### 7.1.2.2 Methods for Ergonomic Analysis

To analyze the ergonomic risk associated in maintaining the oil filter, the team looked into several analysis tools available: OWAS, SNOOK-CIRELLO Tables, NIOSH, OCRA Stain Index HAL-TV, AAWS, and EAWS. The tools can be categorized into First-Level Tools and Second-Level Tools as shown in Table 4.

<table>
<thead>
<tr>
<th>Risk Areas</th>
<th>Standards</th>
<th>Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CEN</td>
<td>ISO</td>
</tr>
<tr>
<td></td>
<td>1005-4</td>
<td>11226</td>
</tr>
<tr>
<td>Body Postures with low external effort</td>
<td></td>
<td>OWAS</td>
</tr>
<tr>
<td>Action Forces</td>
<td>1005-3</td>
<td>SNOOK-CIRELLO TABLES</td>
</tr>
<tr>
<td>Manual Material Handling (Repositioning)</td>
<td>1005-2</td>
<td>NIOSH</td>
</tr>
<tr>
<td>Upper limbs – high frequencies / low loads</td>
<td>1005-5</td>
<td>OCRA STAIN INDEX HAL-TV</td>
</tr>
</tbody>
</table>

The First-Level Tools are designed for quick screening of different ergonomic risk areas. They are designed so that rapid redesigning can be made if necessary. On the other hand,
the Second-Level Tools are designed for detailed analysis, focusing on particular risk areas (Fondazione ERGO-MTM ITALIA, 2013). Since the door designs are in the Designing Phase, it is appropriate to use the First-Level Tools. As a result, EAW, a First-Level Tools that cover four risk areas, was chosen.

7.1.2.3 **Ergonomic Assessment Worksheet (EAWS)**

Developed by the Foundation of ERGO-MTM, the Ergonomic Assessment Worksheet measures the risk associated with various tasks performed during routine maintenance. When creating EAWS, both Machinery-Directive Standard (EN) and Framework-Directive Standard (ISO) were taken into account (Figure 28.) In other words, if the design is considered “Low Risk” by EAWS, it passes EN1005, ISO11226, and ISO11228.

![Figure 28 Framework for Ergonomic Assessment Work-Sheet (Fondazione ERGO-MTM ITALIA, 2013)](image)

EAWS takes into account risks in five areas: Postures, Forces, Loads, Upper Limp, and Extras. Points are assigned to each areas based on the EAWS (Appendix A). Points from Posture Section, Forces Sections, Loads Section, and Extra Section are added to obtain the “Whole Body” Point. The Whole-Body Point is then compared to Upper-Limbs Point; the higher of the two will be used for evaluation shown in Table 5 (Schaub, et al. 2012). The full version of EAWS is shown in Appendix A.
Table 5 EAWS Risk Evaluation

<table>
<thead>
<tr>
<th>EAWS evaluation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-25 Points</td>
<td>Green: Low risk; recommended; no action is needed</td>
</tr>
<tr>
<td>&gt;25-50 Points</td>
<td>Yellow: Possible risk; not recommended; redesign if possible, otherwise take other measures to control the risk</td>
</tr>
<tr>
<td>&gt;50 Points</td>
<td>Red: High risk; to be avoided; action to lower the risk is necessary</td>
</tr>
</tbody>
</table>

7.1.2.4 EAWS Evaluation

For the design’s analysis, only the Postures Section, Forces Section, and Upper-Limbs Section are considered. The Loads Section and Extra Section are not applicable.

Table 6 Maintenance-related information from Caterpillar used in the Ergonomic Analysis

<table>
<thead>
<tr>
<th>Information</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil-Filter Maintenance Time</td>
<td>≤ 5 minutes (8.333% per hour)</td>
</tr>
<tr>
<td>Force to twist Oil Filter</td>
<td>≈ 40N/twist, ≤ 15 twists total (both in and out)</td>
</tr>
<tr>
<td>Density of the door material</td>
<td>7,840 kg/m³ (use to calculate the door weight and force for opening the door)</td>
</tr>
</tbody>
</table>

Table 6, information given by Caterpillar, is used throughout the analysis for all 4 designs. Note that, for safety purpose, the most conservative values are always used.

7.1.2.5 Two-Door Ergonomic Analysis

In order to reduce redundancy only the ergonomic analysis for the two-door mechanism will be discussed in detail. The other design’s scores can be seen without any analysis in section 7.1.2.6 “Results and Evaluation” while the full analysis are located in Appendix A.

7.1.2.5.1 Posture Analysis

The basic position, postures and movements of trunk and arms was evaluated for the design per maintenance shift. Evaluation was based on the static postures and high frequent movements of the trunk and arms, during regular maintenance by the operator as outline by the EWAS worksheet, Figure 29.
For posture analysis, the posture and time (in percent of an hour) are used to calculate the risk point. Posture is identified from the chart (Figure 29 middle left) horizontally, while time is assigned vertically. In addition, if there is an Asymmetry Effects (Figure 29 top right), the risk point will be calculated by multiply interval with Duration (Schaub, et al. 2012).

For the Two Door design, during the maintenance process, there are two postures that the operator needs to take: posture 12 and posture 13. While opening the door, the operator would sit down as posture 12. However, since the time for opening the door is only a few second, 0 is assigned as a risk point. While completing maintenance, the operator will be in posture 13 where the time is, given by Caterpillar, as 8.333%. This translated to 7.33 risk point. In addition, the operator will be performing Asymmetry Effects: Far Reach and Lateral Bending. For Far reach, the intensity is 80% with 8.333% duration, which translated to 3 x 1.13 = 3.39 risk point. For Lateral Bending (use the same scales Trunk), the intensity is 25° with 8.333% per hour duration, which translated to 3 x 1.76 = 5.28 risk point. As a result, the total posture risk point is 7.33 + (3.39 + 5.28) = 16 risk point.
7.1.2.5.2  Force Analysis

The second section the team reviewed was the action forces required by the operator per minute/shift during maintenance (Schaub, et al. 2012). The forces on the fingers, arm and entire body was individually calculated then summed to get the overall risk factor, (Figure 30).

![Figure 30 EAWS Force Analysis of the Two-Door Design](image)

In the Force Analysis Section, the risk point is calculated by multiplying intensity with time (or action). Intensity is calculated by dividing the force used by the maximum force. For our analysis time is replaced by action, the number of actions involved in the maintenance process in order to better represent the tasks involved. Note that when identifying the maximum force, P15 will be used if the force known is an estimated value. On the other hand, P40 will be used if the force is a known value.

While opening the door, the force used is 5N in C’ direction with KN-Upright Posture (115N maximum force). Because 5/115 = 0.0234 is lower than 1/6, the intensity equals 0. Since this design has 2 doors, the number of actions needed to open and close the door is 4, which translated to 2.33 action point. As a result, risk involved in opening the door is 0 x 2.33 = 0 risk point.

While maintaining the oil filter, the approximate force used is 40N/twist. The posture for twisting the oil filter is Posture A1; therefore, the force ratio is 40N/205 = 0.195, which translated to 1.2 intensity point. The number of actions needed to twist the oil filter (both
in and out) is 15, which translated to 2.5 action points. As a result, risk involved in twisting the oil filter is $1.2 \times 2.5 = 3$ risk point.
The total force risk-point is $0 + 3 = 3$.

7.1.2.5.3 Upper Limb Analysis

The maintenance task was also measured based on the load placed on the upper limb during repetitive tasks as outlined in the EWAS worksheet (Schaub, et al. 2012).

The Upper Limb section consists of the Static Action, Dynamic Action, and Grip. In the Static Action Part, it is necessary to identify the force associated with the task (Figure 31 horizontally) then cross-reference it with the time associated with task (Figure 31 vertically). The Dynamic Action Part requires the identification of force (horizontally) as well; however, instead of time, the action/minute is used. The grip is also identified by the force; and then categorized into types: A, B, or C (Figure 31 top left).

For the analysis, “opening/closing the door” is considered a static action while “twisting the oil filter” is considered a dynamic action. In addition, the percent action for both tasks is assumed to be 100% since there is no long interval break between each action.

While opening/closing the door, the force required is 5N and the time required is approximately 36 seconds. As a result, the Static Action Point (FFS) is 3. The grip used to open the door is “grip b”, which has 2 points. The total points are $3 + 2 = 5$. 
While twisting the oil filter, the force used is 40N per action for 15 actions. As a result, the Dynamic Action Point (FFG) is 3. The grip required for twisting the oil filter is “grip a”, which has 0 point. The total point is $3 + 0 = 3$.

The total point for the Upper-Limb section is $5 + 3 = 8$ risk points.

### 7.1.2.5.4 Overall Ergonomic Risk

The Whole-Body Risk Point for maintaining the oil filter with the Two-Door Design is 19; while the Upper-Limbs Risk Point is 8. Since both values are below 25 points, the Two-Doors Design will allow the operator to maintain the oil filter with low risk (Table 7).

**Table 7 Overall Ergonomic Risk of the Two-Door Design**

<table>
<thead>
<tr>
<th>Postures</th>
<th>Forces</th>
<th>Loads</th>
<th>Extra</th>
<th>Upper Limbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>16</td>
<td>3</td>
<td>N/A</td>
<td>8</td>
</tr>
</tbody>
</table>

### 7.1.2.6 Result and Evaluation

By applying the same analysis method to the Zigzag Design, Four Bar Design, and Double Slider-Crank Design, the Risk Points were calculated for each design as shown in Table 8.

**Table 8 Summary of the Ergonomic Analysis for all four designs**

<table>
<thead>
<tr>
<th>Whole Body</th>
<th>Posture</th>
<th>Forces</th>
<th>Loads</th>
<th>Extra</th>
<th>Upper Limbs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Zigzag</strong></td>
<td>19</td>
<td>16</td>
<td>3</td>
<td>N/A</td>
<td>8</td>
</tr>
<tr>
<td><strong>Two-Door</strong></td>
<td>19</td>
<td>16</td>
<td>3</td>
<td>N/A</td>
<td>6</td>
</tr>
<tr>
<td><strong>Four Bar</strong></td>
<td>14.73</td>
<td>11.73</td>
<td>3</td>
<td>N/A</td>
<td>4</td>
</tr>
<tr>
<td><strong>Double Slider-Crank</strong></td>
<td>14.73</td>
<td>11.73</td>
<td>3</td>
<td>N/A</td>
<td>4</td>
</tr>
</tbody>
</table>

The Two-Door Design and Zigzag Door Design, which requires the operator to be in “Posture A” for maintenance has a Whole-Body Risk Points of 19. On the other hand, the Four-Bars Design and the Double Slider-Crank Design, which requires the operator to be in “Posture B” for maintenance has a Whole-Body Risk Points of 14.73. Detailed analysis can be found in Appendix. A.

The result shows that all of four designs are in the Low-Risk Category since both the Whole-Body and Upper-Limb Risk Points are below 25. All 4 doors should allow the operator to safely maintain the oil filter and no redesigning (ergonomic wise) is needed. However, among the 4 doors, the Four-Bars Design and Double Slider-Crank Design will allow the operator to maintain the oil filter more comfortably since the Risk Points are lower.
7.1.3 Cost Analysis

There are 4 factors that contribute to the total cost of each design: Laser Cutting Cost, Material Cost, Standard Part Cost, and Custom Part Cost. In this section, we will explain how the each type of cost is calculated. Table 9 shows the summarization of the cost analysis for all designs. For more detailed calculation, please refer to in Appendix B.

7.1.3.1 Laser Cutting Cost

The laser-cutting cost is one of the two primary cost for manufacturing the door. It is calculated by multiplying the parameter of the door by the laser cutting service rate. For the analysis, the rate is $0.059/cm (Pololu.com). The laser-cutting costs of each design are shown in Table 9.

7.1.3.2 Material Cost

The material cost is calculated by multiplying the weight of the door by the steel cost. The material cost was estimated to be approximately $1/kg. The material costs of each design are shown in Table 9.

7.1.3.3 Standard Part Cost

The standard part cost is calculated by adding the cost of parts from Caterpillar’s main supplier. Note that the retail prices (of parts in the same family) were used for calculation, since the actual prices are restricted information. The standard-part costs of each design are shown in Table 9 (Amazon.com, 2013).

7.1.3.4 Custom Part Cost

The custom part cost can be calculated by adding the custom material cost with the labor cost (Hua, 2013). The custom material cost is calculated based on the weight of raw material (cubic, cylinder, or metal sheet) used to make the custom part. The labor cost is calculated based on the estimated time used to manufacture the part. For the analysis, the labor wage for manufacturing technician is $15.625/hour (Indeed.com, 2013). The custom-parts costs of each design are shown in Table 9. For detailed calculation of the custom part cost, please refer to Appendix B.

7.1.3.5 Total Cost and Relative Cost

Note that, for the analysis, all costs are calculated based on retail cost in the United States. When Caterpillar manufactures the designs, the manufacturing cost will be a lower due to lower manufacturing cost in China and the economy of scale. As a result, in order for the analysis to be useful, the relative cost of the door was calculated based on the regular door design that Caterpillar is currently using. The relative costs of each design are shown in Table 9. The relative cost, from lowest to highest, are as follows:
Zigzag Door Design, Two Door Design, Four Bars Design, and Double Slider-Crank Design respectively.
Table 9 Summary of Cost Analysis

<table>
<thead>
<tr>
<th></th>
<th>Regular</th>
<th>Zigzag</th>
<th>Two Door</th>
<th>Four Bar</th>
<th>Double Slider-Crank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Cutting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length (cm)</td>
<td>376.90</td>
<td>452.53</td>
<td>494.02</td>
<td>376.90</td>
<td>371.21</td>
</tr>
<tr>
<td>Laser Cutting Cost</td>
<td>$22.60</td>
<td>$26.72</td>
<td>$29.17</td>
<td>$22.26</td>
<td>$21.92</td>
</tr>
<tr>
<td>Material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>23.10</td>
<td>12.16</td>
<td>13.03</td>
<td>23.31</td>
<td>35.00</td>
</tr>
<tr>
<td>Material Cost</td>
<td>$23.10</td>
<td>$12.16</td>
<td>$13.03</td>
<td>$23.31</td>
<td>$35.00</td>
</tr>
<tr>
<td>Standard Parts</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parts</td>
<td>Lock #1 (15.58<em>1) Hinge #1 (6.43</em>2)</td>
<td>Lock #1 (15.58<em>1) Hinge #1 (6.43</em>4)</td>
<td>Lock #1 (15.58<em>1) Hinge #2 (6.43</em>4)</td>
<td>Lock #2 (23.04*2)</td>
<td>Lock #2 (23.04*1)</td>
</tr>
<tr>
<td>Standard Parts Cost</td>
<td>$28.44</td>
<td>$41.30</td>
<td>$41.13</td>
<td>$46.08</td>
<td>$23.04</td>
</tr>
<tr>
<td>Custom Parts</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material Weight (kg)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6.84</td>
<td>16.45</td>
</tr>
<tr>
<td>Material Cost</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6.84</td>
<td>$16.45</td>
</tr>
<tr>
<td>Labor Time (hr)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.83</td>
<td>16.56</td>
</tr>
<tr>
<td>Labor Cost</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$28.65</td>
<td>$258.85</td>
</tr>
<tr>
<td>Total Custom Parts Cost</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$35.48</td>
<td>$275.30</td>
</tr>
<tr>
<td>Total Cost</td>
<td>$74.00</td>
<td>$80.18</td>
<td>$83.51</td>
<td>$127.13</td>
<td>$355.26</td>
</tr>
<tr>
<td>Relative Cost</td>
<td>1</td>
<td>1.08</td>
<td>1.13</td>
<td>1.72</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Laser Cutting Cost = $0.059/cm
Material Cost = $1/kg
Labor Cost = $15.625/hr
7.1.4 Design Pro’s and Con’s

After the CAD models of the designs were complete a pro and con list was made for each design to do the original comparisons. After making the lists and doing the compressions there were three designs left for further analysis. The pros and cons lists are outline in Table 9 below.

<table>
<thead>
<tr>
<th></th>
<th>+ Pros +</th>
<th>- Cons -</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zigzag</td>
<td>Small enough to open within the space limitation</td>
<td>Due to the gap required for the hinges, the door will have sealing and vibration issues</td>
</tr>
<tr>
<td></td>
<td>Cost effective</td>
<td>The door is hard to constrain without using a sliding track. However this is not an option because of the shape of the frame</td>
</tr>
<tr>
<td></td>
<td>Easy for operator to understand how to use it</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Light weight</td>
<td></td>
</tr>
<tr>
<td>Two- Door</td>
<td>Cheapest model</td>
<td>There may be vibration issues between the two inter locking doors</td>
</tr>
<tr>
<td></td>
<td>Corrosion resistant</td>
<td>Sealing issues may arise</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low weight</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Four Bar Mechanism</td>
<td>Small enough to open within the space limitation</td>
<td>Due to the nature of the bars there may be vibration problems</td>
</tr>
<tr>
<td></td>
<td>Will not interfere with worker while providing service</td>
<td>When the door is open the bar may interfere with the inner workings of the loader. This cannot be determined from the model received from Caterpillar as there is nothing</td>
</tr>
</tbody>
</table>

Table 10 Pros and Cons List of each design
<table>
<thead>
<tr>
<th>Easy to manufacture</th>
<th>High cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easy for operator to understand how to use it</td>
<td>Potential sealing problem near the door hinge</td>
</tr>
<tr>
<td>Corrosion resistant</td>
<td>Very heavy</td>
</tr>
</tbody>
</table>

**Double Slider-Crank**

<table>
<thead>
<tr>
<th>Small enough to open within the space limitation</th>
<th>Most expensive design</th>
</tr>
</thead>
<tbody>
<tr>
<td>No interference when opening the door</td>
<td>Many special parts</td>
</tr>
<tr>
<td>Can easily be sealed with rubber</td>
<td>Clearance eliminating mechanism are going to increase the cost</td>
</tr>
<tr>
<td>There are stiffeners behind the door to eliminate access vibration</td>
<td>DOF will make it harder for the operator to control the door when opening and closing</td>
</tr>
<tr>
<td>Can open fully giving workers more space to work than all other designs</td>
<td>Extremely heavy and will require a large amount of force to open</td>
</tr>
<tr>
<td>FEA analysis shows that the crank and hinge can both withstand the weight of the door</td>
<td>May have durability and life expediencies issues</td>
</tr>
<tr>
<td>Safety factor for both the hinge and crank are above 1</td>
<td>Slider may have material issues</td>
</tr>
<tr>
<td></td>
<td>No sliders currently be manufactured</td>
</tr>
</tbody>
</table>

### 7.1.4.1 Zigzag Door

In theory the zigzag door is a good design to combat the space constraints, the originally proposed problem, but there are also many flaws that were not initially realized. The flaws found quickly ruled the design out of the running for the final design. The door was not able to properly seal, therefore it would not protect against the outside environment, and would also led to high level of vibration. For sealing the team looked into multiple options including; weather-stripping, and use of an additional piece of steel backing on one of the doors. Weather stripping is a common type of pressure seal, known as a dynamic seal used in all cars, it is the black material found around door and window frames. Pressure seals are used to make the interface between two moving components, which is why it is classified as dynamic seal and not static, tight and secure against their surroundings. They are also used to limit the amount of fluid flow between the two surfaces. Depending on the properties of the materials being sealed an O-Ring, V-ring or rectangular seal may be selected (Black, 2007). The other main option looked into was
adding a small piece of steel to the back end of one of the doors so that it sealed the opening between the two of them when closed, an example of this is shown in Figure 32 below.

![Figure 32 Example of extra backing for bi-fold door](http://www.homeartblog.com/bi-fold-doors)

After much research and modeling in CAD it was realized that these options are very good options for basic doors. However they were not great ideas for door used in extremely dirty, dusty environments where the loader was going to be placed under extreme conditions producing lots of noise and vibrations. The seal provided by either option did not provide a good enough seal to fight against the access vibration that would be produced during normal operation, at speeds 5mph in the underground environment. This access vibration would produce high levels of noise which was one of the main things that Caterpillar wanted to make sure was avoid in any of our designs.

Another issue that arose was how to constrain the door to make it function properly. Most zigzag doors use a sliding mechanism to constraint them to move back and forth with the space required an example of this can be seen in Figure 33.

![Figure 33 Example of bi-fold closet door](http://www.thisoldhouse.com/toh/how-to/intro/0,,1176649,00.html)
If the door is not placed on sliders the results is a door that has two fully functioning hinges allowing it to fully unfold to 100 percent in length. This would not be ideal for the design, as it would not provide much of a solution to the space constraint issue. However placing the door on a set of sliders was not a viable option either. Located 325 millimeters above the oil filter is the Turbo Engine, which runs at extremely high temperatures and would quickly dry up any lubrication needed for the slider to run properly. Other options such as sliders with a series of balls placed on the inside of the track for the door to roll over was looked into, but this was going to be very costly and it also required lubrication to work properly. One of the team’s original 6 designs used this method but it was discounted for above listed reasons.

7.1.4.2 Two Door

The two-door was the cheapest of the design, which was a major advantage, because it would be most appealing to customers. Due to its simplicity and basic design the door was lightweight, not much heavier then what was already in use, and using SolidWorks analysis the hood would definitely be able to withstand its’ weight. The door is also compact enough to open fully within the space constraint, but more so here the two doors will open up and fully expose the oil filter on both sides giving adequate space for service. The two-door design however has some major flaws that may be hard to overcome.

The nature of the doors will not allow the door to securely close, without additional measures such as weather stripping. Even with weather stripping it is unknown if the door will be able to close securely enough to keep out excess debris. The major issue here though is the vibration that will be caused by the interlocking doors in the middle. The hinge in the middle will be the major issue and will be extremely hard to overcome because it is necessary for this design.

7.1.4.3 Four Bar

The four-bar mechanism is one of the most common and simplest linkages, and when used to open the door has both advantages and disadvantages. However, due to its unique and custom nature it will be one of the more costly designs. The four bar mechanism has three main advantages that make it a viable solution to the proposed problem. The actual door is small enough to open within the limited amount of space provided between the hood and the ladder, and it is still large enough for the operator to easily provide service to the oil filter. There will be no interference between the operator and the door or mechanism when service is being administered keeping the operator safe. This means that during service the operator will not be anywhere near the turbocharger, ideally eliminating any safety concerns. It is also easy for operators to understand and will not require any sort of special training or paperwork prior to operation.

There are also a few flaws with the design that will need to be work out if used in production. Vibration issues will arise due to the large bars needed to create the linkage. The bars are made from steel so during operation the turbulence created will cause the
bars to move clanking against the door also made from steel producing excess noise. Another potential problem is that when the door is opened and the bar bent inward there may be a collision issue with some of the inner workings with the loader. This however cannot be proven as the team has an empty model, but if were an issue it could easily be solved by modifying the linkage slightly as to not change its path too much. Lastly, there is a hard to solve sealing issues between the linkage and the hood, Figure 34. This gap will allow large amounts of debris into the inside of the tractor and will also cause large amounts of noise due to vibration.

Figure 34 Gap formed between the hood and mechanism in the Four Bar design

7.1.4.4 Double Slider-Crank

The Double Slider-Crank is the most unique and expensive of the designs and has some major advantages and disadvantages associated with it. Without any modifications to the initial model the device would be a 480% cost increase from Caterpillar’s current model is. For obvious reasons a design with such an increase in price is not workable, so some modifications will need to be made. Even with the drastic price increase the design has enough positives that it needs to be kept in the running for final designs.

A major plus of the double-slider crank is that it is a unique out of the box design that Caterpillar was looking for. The mechanism is compact, making it small enough to fully open within the space constraint provide without interfering with any other parts of the loader. Also, since the door can fully open there is adequate room for the operator to perform maintenance with no possible interference with the turbo-charger. Both the vibration and noise are significantly limited in the design. A small piece of rubber weather-stripping will be used to seal the door decreasing the amount of vibration that can occur and decreasing sound transmission. Behind the door, not the four bar mechanism, there are stiffeners that will make the door stronger and will decrease any (if not all) excess vibration.
Disadvantages of the mechanism revolve mainly around its uniqueness. Caterpillar’s does not currently have any sliders, thus increasing the price. The slider has 21 custom parts that Caterpillar will need to manufacture, increasing the price, time and complexity of the product. The mechanism is also extremely heavy because it is made form sold steel. The weight of the door combined with the Double Slider-Crank mechanism, could potentially cause durability and life span issues.

7.1.5 Stage Two-Utilization of the Design Matrix

Stage two was utilizing the design matrix for a more through design comparison. Each design was analyzed on its performance, ease of use, cost and reliability and summed in Table 11 below.

Table 11 Completed Design Matrix for all designs

<table>
<thead>
<tr>
<th>Priority Ranking</th>
<th>Reliability</th>
<th>Ease of Use</th>
<th>Performance</th>
<th>Cost</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zigzag</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>9</td>
<td>30</td>
</tr>
<tr>
<td>Two Doors</td>
<td>9</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>108</td>
</tr>
<tr>
<td>Four Bar</td>
<td>3</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>84</td>
</tr>
<tr>
<td>Double Slider-Crank</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>1</td>
<td>136</td>
</tr>
</tbody>
</table>

7.1.5.1 Reliability

It was important to make sure that the designs were reliable and would have an extended shelf life. To due this the team reviewed the pros and cons of each design and used SolidWorks to make sure that the door and its mechanism could be support by the hood to avoid failure.

7.1.5.1.1 Zigzag Door

The zigzag door was given a design ranking of 1 for reliability, because of the fore mentioned reasons. If the door cannot meet the basic needs such as sealing it is not going to be a reliable design because it will provide more problems in the long run for Caterpillar. Without a proper seal water and debris can get through the door and into the inside of the loader and get into the oil filter, turbo engine and other curial parts needed for it to run correctly. Water and debris in these parts will require more frequent service and money for replacement parts and operators and may even lead to termination of the loader. Also, if the design cannot limit the amount of vibration within the door there will be issues with noise, wear, breakdown and finally failure of the door.
7.1.5.1.2 Two Door
The two door design received nine points for reliability. The mechanism is lightweight and can easily be supported by the hood and loader. The two doors are small enough to open within the space provided and open up at the center exposing the oil filter with ample room on either side. With ample room the operator will not be anywhere near turbocharger during service keeping them safe and out of harm’s way. With extra weather-stripping the door will be able to seal and keep out debris. The only issue with the reliability of the door is the possible issue with vibration. This should not be a large issue to overcome and in the final design should not be a huge problem.

7.1.5.1.3 Four Bar

The four bar design received a reliability score of 3, not as good as the two door but better than the zigzag door. The four bar linkage has long bars to make it move in the proper path. These bars are heavy and due to the weight will make it harder for the loader to support. Yes it was established that the loader can maintain the weight but it will fail sooner than some of the other designs. Another issue with the design is the sealing issue between the door and the hood which is going to be challenging to overcome. If the design cannot meet all the general needs of the customer it cannot be endorsed as reliability. This design does meet most of the needs which is the reason it received 3 ranking points and not 0.

7.1.5.1.4 Double Slider-Crank

The Double Slider-Crank only received 1 point for reliability. Due to the fore mentioned cons the design cannot be seen as reliable. The door has a couple of main issues that will reduce its reliability. The door is hard for the operator to control, which could lead to safety issues. The main issue however is the fact that the door has sliders, which will overtime get junked up with debris and make the slider no longer to slide. If the design were to move on in the design process there would need to be a measure taken to overcome this issue. At this point without any modifications the door does not have a long shelf life because of the sliders.

7.1.5.2 Ease of Use

The ease of use is calculated based on the ergonomic analysis of each design as previously explained. In Table 12, a summary of Ease of Use rating for all four designs is outlined. In addition, a brief evaluation is explained in this section.

<table>
<thead>
<tr>
<th></th>
<th>Whole Body</th>
<th>Upper Limbs</th>
<th>Risk Level</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zigzag</td>
<td>19</td>
<td>8</td>
<td>Low</td>
<td>3</td>
</tr>
<tr>
<td>Two-Door</td>
<td>19</td>
<td>6</td>
<td>Low</td>
<td>3</td>
</tr>
<tr>
<td>Four Bar</td>
<td>14.73</td>
<td>4</td>
<td>Low</td>
<td>9</td>
</tr>
<tr>
<td>Double Slider-Crank</td>
<td>14.73</td>
<td>4</td>
<td>Low</td>
<td>9</td>
</tr>
</tbody>
</table>
7.1.5.2.1 Zigzag Door

Even though the Zigzag Door design is considered ergonomically safe since it has a Whole Body Risk Point of 19. However, the Risk Point is still higher than other designs’ Risk Point because the operator has to maintain the oil filter in Posture A. As a result, 3 is given for Ease of Use Rating.

7.1.5.2.2 Two Door

Like the Zigzag Door, the Two Door requires the operator to maintain the oil filter in Posture A. Note that, due to an easier opening mechanism, the Upper Limbs Risk Point is a little lower than the Zigzag Door’s. A rating of 3 is given for this design as well.

7.1.5.2.3 Four Bar

The Four Bar has a Whole Body Risk Point of 14.73, which is the lowest among our designs. This is because the operator is able to maintain the oil filter in Posture B, which is a more comfortable posture. As a result, 9 is given for Ease of Use Rating.

7.1.5.2.4 Double Slider-Crank

The Double Slider-Crank has the same Risk Point with the Four Bar’s. This is because the operator is required to sit in Posture B while maintaining the oil filter. In addition, even though, the mechanism for opening the door is not the same as Four Bar’s, the posture while opening the door is the same. As a result, a rating of 9 is given as well.

7.1.5.3 Performance

The design’s performance reviewed based on the guidelines outline in section 6.1.4.1 measuring performance.

Table 13 Evaluation of performance

<table>
<thead>
<tr>
<th></th>
<th>Corrosion Resistant</th>
<th>Size Efficient</th>
<th>Vibration</th>
<th>Sealing</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zigzag</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Two Doors</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Four Bar</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Double Slider</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>6</td>
</tr>
</tbody>
</table>
7.1.5.3.1 Zigzag Door

The zigzag door meets two out of the four possible design goals, and was rewarded two goal points accordingly corresponding to a design ranking of 1. The design was considered to be corrosion resistant, receiving a design goal of 1, as the material used is the same material currently used by Caterpillar. The door is also able to freely move within the space provided without interfering with any other parts of the tractor, receiving a ranking of 1 for size efficient. The door failed in the categories of vibration and sealing receiving rankings of 0.

7.1.5.3.2 Two Door

The two door design received four total goal points, corresponding to a design ranking of three. The material of the design is the same as what Caterpillar is using and is thus considered to be corrosion. Using the CAD model it was determined that the door could be opened within the space constraint with adequate room, again receiving a design score of 1. As stated in the pro and cons the hinge in the middle of the door will produce vibration, however using weather-stripping in conjunction with a rubber block at the bottom of each door some of the vibration will be limited, therefore scoring a design goal of 1. Lastly, the issues with sealing only allowed the team to reward the category a goal score of 1, because without any modifications the door will seal but will allow debris to enter the chamber.

7.1.5.3.3 Four Bar

The four bar mechanism meets all of the design goals but does not exceed expectations and received 4 total goal points. Consistent with all other designs the mechanism is both space efficient and is considered to be corrosion resistant. Due to the length of each link used for the four bar mechanism there may be some excess vibration produced when the loader is operating, which is why it was only considered to meet expectation. Lastly, the four bar mechanism as stated above will have some minor sealing issues between the side of the hood and the hinge on the door causing minor sealing issues, therefore receiving one goal point for sealing capability.

7.1.5.3.4 Double Slider-Crank

The double slider received a perfect score meeting and exceeding all criteria and thus was rewarded four goal points for performance. The double slider mechanism will allow the door to securely shut and seal, (extra weather-stripping will be needed to keep out debris) exceeding design goal expectations and receiving 2 goal points for both criteria. Like the other design the door and mechanism is considered to be corrosion resistant because it is made from the same material utilized in Caterpillar’s current design. Lastly, one goal point was rewarded for size efficiency because the door is small enough to open within the space constraint provided, unique to this design is the fact that the door can open fully giving the operator amble room to perform service.
7.1.5.4 Cost

The rating for cost is based on the analysis performed in section 7.1.3 “Cost Analysis”. Table 13 shows the total cost, relative cost, and cost rating for all four designs. An evaluation is also explained in this section.

Table 14 Cost Rating based on Cost Analysis

<table>
<thead>
<tr>
<th></th>
<th>Total Cost</th>
<th>Relative Cost</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular</td>
<td>$74</td>
<td>1</td>
<td>N/A</td>
</tr>
<tr>
<td>Zigzag</td>
<td>$80.18</td>
<td>1.08</td>
<td>9</td>
</tr>
<tr>
<td>Two Doors</td>
<td>$83.51</td>
<td>1.13</td>
<td>9</td>
</tr>
<tr>
<td>Four Bars</td>
<td>$127.13</td>
<td>1.72</td>
<td>3</td>
</tr>
<tr>
<td>Double Slider-Crank</td>
<td>$355.26</td>
<td>4.8</td>
<td>1</td>
</tr>
</tbody>
</table>

7.1.5.4.1 Zigzag Door

The Zigzag Door is the cheapest door among all designs. This is because, compared to the Regular Door Caterpillar is using, the Zigzag Door’s cost of material is lower. The only major cost increase of the Zigzag Door is from two addition standard parts (Hinges). The total cost of the Zigzag Door is $80.18, which is 1.08 times the Regular Door. As a result, the Zigzag Door is given a rating of 9.

7.1.5.4.2 Two Door

The Two Door is the second cheapest door. Like Zigzag Door, the material cost of the Two Door is lower than the Regular Door because of the smaller size. The additional cost is also from the two extra standard parts (Hinges). The total cost of the Two Door is $83.51, which is 1.13 times the Regular Door. With the relative cost close to 1, the Two Door is given a rating of 9 as well.

7.1.5.4.3 Four Bar

The manufacturing cost of the Four Bar Design is relatively high even though the laser cutting cost and material cost are equal to the Regular Door’s. The Four Bar Design requires a total of 4 custom parts which cost approximately $35.48 extra. This brings the total cost of this design to $127.13 – 1.72 times the Regular Door. As a result, the Four Bar Design is given a rating of 3.

7.1.5.4.4 Double Slider-Crank

Due to the high number of custom part, the Double Slider-Crank is our most expensive design. The custom parts alone cost $275.3, which bring the total cost to $355.26 (4.8 times the cost of Regular Door). As a result, the Double Slider-Crank is given a rating of 1.
7.2 Caterpillar’s Feedback

The team went and presented the four final designs along with the pros and cons of each one to Caterpillar for feedback and final design selection. Also presented were the CAD models of each design and the previously stated mechanical analysis. Overall the feedback from Caterpillar was positive and a great aid in the decision process.

7.2.1 Zigzag Door

The zigzag door was favorably review by both Danny and Brad at Caterpillar. Danny the engineer working on the same project within the company, has proposed a very similar solution to this one previously, but is having similar issues to that posed by the team. The main difference between the team’s design and Danny’s design is the location of the door. Danny’s design uses a full door located on the right side of the hood instead of a center door. Caterpillar has this design in the optimization stage, but is having issues solving the vibration produced by both the hinges and door panels. One piece of information that was given specific to the design the team proposed was to make sure the oil filter is not hit by the hinges when the door is opened and closed. The team and Caterpillar came to a general consensus that the zigzag door, with modification to the center door concept, is a viable solution but needs a great deal of work into the vibration issue.

7.2.2 Two Door

Due to the simplicity of this design Danny was in favor of this one. Danny comments were that simple is better; it is easier to produce, use and is overall cheaper, and that it will do the job just fine. The drawback to this design is its simplicity Caterpillar was looking for a new and innovative design, so this does not quit fit the description they were after.

7.2.3 Four Bar

The design received mixed reviews, similar to when the team reviewed it. The general concept behind the door was well received and liked. The main concern with this door was its overall strength. Both engineers agree that the hood and hinges may be able to support the door’s weight, but will it be able to support more weight? The concern is that if the operator slips and grabs onto the door for support the door may come down with him. As one could see this would be a huge liability issue.

7.2.4 Double Slider-Crank

The double-slider crank received the best reviews, because of it out of the box unique nature. Brad said that the design is ready for the optimization and perfection process, as long as a few minor flaws can be worked through. The main concern with the design is manufacturing and its cost, as it stand the cost would be too high for Caterpillar to produce. The other issue is the life expediency of the slider mechanism.
Even though this is a custom model, cost and simplicity is still an important factor to be considered in the design. Most of the parts used for the slider are custom and cannot be purchased by Caterpillar. This was a large red flag for Brad. Brad suggested that the team make a slightly simplified version of the design, trying to utilize more standard parts. Two suggestions were to replace the slider with a simple guide, and to substitute in simple wheels, both would greatly reduce the cost. It was also noticed that because of the sliders there may be some issues during the welding process. To bypass the issue with the welding it was suggest that the doors support be modified to a triangle instead of a trapezoid, so that laser cutting could be used instead. Lastly, there may be an issue during the painting of the loader, as the wheels cannot be painted because of their material. However the wheels can simply be zinc plated instead. By making slight modification to the current design both the manufacturing process and cost can be reduced.

The slider may have some life expediency issue, also increasing the cost if it needs to be frequently replaced. As previously mentioned under to hood near the oil filter is a turbocharger and turbine to boost the engine’s power. The turbine works like a vacuum sucking up air from the outside, but with that air comes lots of debris, dust and particles. The debris would easily get stuck in an open slider causing build up and if not properly taken care of would eventually destroy the mechanism. Brad does not want to take a gamble with this and suggest that the team look into ways to prevent this from happening.
8 Final Design

After speaking with both Danny and Brad it was decided that the double-slider crank was the overall winner, but needed some work done to make it to the production process. The team closely reviewed the design looking into ways to simplify the mechanism to reduce the cost and improve its life expediency.

Figure 35 Isometric view of the loader with Double Slider-Crank design

Figure 36 Final door design showing sider and guide mechanism

Figure 37 Exploded view of the slider with all of its components
Figure 38 Detailed view of the slider

Figure 39 Von-Mises of the slider base
Figure 40 Safety factor of the slider base (FEA)

Figure 41 Von-Mises of the hinge (FEA)
8.1.1.1 Double Slider-Crank Cost Reduction

The double-slider crank proposed to Caterpillar had a cost increase of roughly 480%. This increase was due primarily to its unique nature requiring specially manufactured parts. In order to decrease the cost, and simplify the design the team proposed four design modifications.

1. Modify the support structure on the door from a trapezoid shape to a triangle shape. Changing the shape provides multiple functions. Using a triangle support will allow for laser cutting to be used for the guides versus welding (as with the trapezoid). Laser cutting is much cheaper and more accurate the welding. Welding requires a great deal of training and precision, as it is done my hand at Caterpillar, leaving a lot of room for human error. The triangle support will also reduce the amount of material needed therefore further reducing the production cost.

2. Replace the current sliders made from solid steel to sliders composed of Polytetrafluoroethylene, PTFE, (Teflon) with a steel core for additional strength. When most people think of Teflon they think of cookware, because it is a common coating on many non-stick pans. Teflon is actually a registered trademark and brand name owned by DuPont. Teflon is a family of high-performance products that are used in wide range of applications, composed of PTFE a high-performacne fluoropolymer (“What is Teflon”) The slider would be
made from PTFE, it does not specifically need to be made from Teflon however. The PTFE slider would have the same non-stick slippery characteristic as Teflon, and because of this there would be no need to use wheels like with the steel sliders. Not using wheels may significantly reduce the cost of the sliders. Depending on the manufacturer Caterpillar uses the cost of using PTFE versus steel will very, but on average it appears that PTFE is a little less expensive (over 10 manufactures were looked at).

One problem that may arise is the overall strength of the new slider. PTFE is a fluorocarbon-resin dating back to 1938, made by polymerizing tetrafluoroethylene. It has an extremely high melting point, so no need to worry about the excess heat from the turbo charger, of 327°C therefore never fully melting requiring special shapes to be machined versus molded(Gooch, 2007) (like in the sliders case). There are many factors that will influence the overall performance of PTFE including; degree of orientation, molecular weight, extent of microporosity, percent crystallinity, and presence of macroscopic flaws. Special testing is done to make sure the PTFE is up standards before being sold this testing includes: heat of fusion, ultimate elongation, specific gravity testing, dielectric strength, and tensile strength. By using the proper ratio of steel to PTFE finding a block with proper strength will not be a problem. Also, depending on the cost from Caterpillar’s manufacturer it is also possible to make a solid steel block with a PTFE coating to obtain PTFE’s desired properties.

Other advantages of PTFE include: virtually unaffected by weather, low coefficient of friction, stability at high temperatures, nonadhesiveness, nonflammability, nonsolubility and chemical resistance to corrosive reagents.

3. Modify the wheels on the slider. The current wheel designed could be simplified to reduce the cost of manufacturing and materials. The wheels clearance fit could be changed to fit to the pin on the wheel module. By doing this it would simplify both the 96 rolling pin component of the wheel as well as the inner part. By reducing the clearance fit it may make the wheel harder to move because of the tight nature. To overcome the new rolling issued the wheels could be coated in PTFE or PE.

4. Modify the pin between the crank and the slider to be clearance fit on their own without the need of the clearance elimination mechanism. The design change would simplify the two bearings used and the bearing cups and eliminate the need for precisions holes to be cut. It would also eliminate the use of the clearance elimination mechanism, a specially designed part.

Eliminating the mechanism would greatly reduce the cost of the product, but may lead to some minor issues at first. Such as with the modification of the wheels there may be some tight fit issues making to door harder to move. This however may be simple to overcome by using a gasket made from PTFE or PE, which both have a low coefficient of friction allowing them to slid easily.
8.1.1.2 Improved Life Expediency of Slider

The loader will be used in underground steel mines and coal mills both extremely dirty environments with a lot of debris and particles floating around. The debris and particles will get into the guides on the door and if not properly taken care of debris will build up causing issues for the door. The only foolproof way to fight against this problem would be to add an additional component to the service work order. When servicing the oil-filter it will also be necessary for the operator to clean out the guides on the door so that debris is removed and the door continues to open properly.

9 Reflection on the Project (Peerapas Thongsawas)

9.1 Design Component

Our team developed new solutions to solve the space limitation problem between the door and the ladder for Caterpillar. The process started from brainstorming ideas to creating implementable models. As a result, our team utilized both mechanical-engineering design component and industrial-engineering design component. The first mechanical-engineering design component is creating four mechanical designs using CAD. Our team transformed possible ideas into the following CAD models: Two-Door design, Zigzag Door design, Four Bar design, and Double Slider-Crank design. Second, we performed mechanical analysis on Four Bar design, and Double Slider-Crank design. Finally, we created a design matrix to evaluate our designs. The criteria we used for the design matrix are: Reliability, Performance, Ease of Use, and Cost.

For the industrial-engineering design component, our team performed Ergonomic Analysis, Sourcing, and Cost Analysis. When creating CAD models, we took into account of what posture the operator will use to maintain the oil filter. We made sure that our four final designs pass the industry standard and does not cause discomfort to the operator. After the designs were created, our team used EAWS to perform an ergonomic analysis to confirm that all designs are safe and no redesigning is needed. In addition, when creating the designs, sourcing were taken into account in order to maximize the use of standard parts; therefore, minimize the cost. Finally, we perform cost analysis. The analysis used four components to estimate the cost for each door design: Laser-Cutting Cost, Material Cost, Standard-Part Cost, and Custom-Part Cost. The cost analysis allow us to provide Caterpillar with an estimated relative cost for all four new designs – compared to Caterpillar’s Regular design.

9.2 Constraint

When creating the designs, safety was the most important constraint to Caterpillar. In order to comply with the loader safety standard, ISO2867, ISO3457, and ISO20474 were used as a minimum safety requirement. By complying with these standards, Caterpillar will be able to create safe designs and manufacture them in any of its plants, regardless of location. In addition, we used EAWS to guarantee that our designs will pass ISO11226,
ISO11228, and EN1005. These standards not only confirmed that our designs are safe but also confirmed that the operator will be able to use our designs without any discomfort. Another constraint we faced is the limitation of Caterpillar’s supplier. Since, Caterpillar has a main supplier for standard parts, we were requested to only use standard parts from the main supplier in order to minimize the cost. As a result, when creating the designs, we had to make modifications to accommodate the use of those part. Finally, the last constraint we encountered was limitation of information. Caterpillar was not able to share its financial-related information with us since it’s considered a trade secret. As a result, when performing cost analysis, we have to create our own cost model and use relative cost to best estimate the manufacturing cost of each design.

9.3 Need for life-long learning

Working on an internationally-collaborated project with Caterpillar and Shanghai University had been professionally enlightening. As an industrial engineer, I was able to apply knowledge learned at WPI to a project in a professional setting. Specifically, creating a cost model and performing cost analysis was based on knowledge learned in Data Analysis for Decision Making (BUS2800) and Engineering Economics (OIE2850) while sourcing was based on knowledge learned in Global Planning and Logistics (OIE4460). On the other hand, some topics which were needed for the project are not covered in WPI’s Industrial Engineering Program; therefore, they were self-taught during the project. These topics include human factors and performing ergonomic analysis.

There are also several challenges I faced during the project. First, since this project involves a lot of mechanical-engineering design component, it was necessary that I learned about the mechanical design process from the start to the end. The second challenged I faced during the project was the cultural difference. I learned that or Chinese partners have a very different working style than WPI students. From my experience, most WPI students prefer to make preparation ahead of time and use short meetings as a platform for discussion. However, our Chinese partners prefer to work together in long-session meetings. By learning about cultural difference and working styles, by the second week, our team was able to create an efficient work group that accommodate both working styles. The third challenge was an unexpected situation. One of our WPI team member had to go back to the United States during the third week of the project. As a result, we set up a weekly conference call to accommodate our member to work from distance. Finally, the last challenge was the limitation of the advisor’s availability. As a result, our team had to be a lot more proactive and resourceful than others.

Working on this project, I have developed several skills professionally. Like most projects in real life, our project needed knowledge from several disciplines to create a practical solution. Learning mechanical-engineering design component has broaden my perspective and problem-solving approach. In addition, there can be a lot of uncertainties involved in a project. It is very important that the students learn to be resourceful and be flexible enough to solve the problem regardless of the circumstance. Finally, I learned that to successfully manage a project, it’s important to take “human-related” factors into consideration and create a process that accommodate the need of every member in the
project. Working on the Major Qualifying Project had prepared me to work in a professional setting. By continuing to acquire knowledge from other disciplines, taking into account of risks and uncertainties, and being considerate to people’s need, I will be able to continue improving myself professionally.
10 References


Dupont. Teflon® PTFE fluoropolymer resin Properties Handbook USA.


