Design and Analysis of New Flexible and Safe Forklifts

Abstract

In today's life, there is a wide variety of forklifts, from the large heavy loading truck to the one that works among narrow aisles. Forklifts have become one of the basic transportation tools we use in our lives. With all the forklifts in existence, we find that there are some improvements that can be made to bring the forklift to a better performance.

Existing forklift design has its limitation in rotation and the structure has potential safety risk. Our new design has 180 degrees rotating forks attached to truck body on both ends. Also, it has a scissor lift under the operator’s cabin which improves the stability. There are two subassemblies: scissor lift and lifting fork; there is a total of 37 parts in the new design.

Once the design is conceived, we calculate the mass properties of parts and subassemblies to ensure the stability of the forklift. Results show that the truck is safe to use: its center of gravity remains in the safety triangle and we use this to get the maximum loading capacity. Then we run stress analysis on important parts and subassemblies using finite element method (FEM). Results show that the new design is safe to use under working conditions.
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Chapter 1 Introduction

1.1 Overview

Because of the varieties, different shapes, different packaging of the goods, loading and unloading has always been a heavy process during transportation. Forklifts were naturally invented and became the solution to this problem; they save time and space. If cargos are being organized properly, the use of forklifts with the right attachments would be the best way to load and unload, which would make the whole process less time consuming and less labor intensive. In addition, forklifts optimize the use of storage space by eliminating the need for many people to handle the loading and unloading operations and enabling the stack-up of goods. The stacking height of goods can be up to 4~5m, some even can be as high as 10m, which brings up the utilization of warehouse by least 40%. Now, most of the transportation operations are using forklifts.

Forklifts fall under the category of lifting and transport machinery. A forklift has a lifting system for loading packages and a mobile system for moving around, like a truck. A forklift is also called a forklift truck. It is mainly used for loading and unloading common packaged goods. With some special attachments, it can also be used for non-packaged goods or untraditional shaped good. Figure 1.1 shows a forklift equipped with
attachment picking up a roll of paper. This hydraulic clip attachment allows the operator to open and close a clip around a load. Products like cartons and boxes can use this type of attachment. Figure 1.2 shows a forklift with a special attachment allowing the rotation of the load.

Figure 1.1 Forklift with Paper Handling Chassis [1]

Figure 1.2 Hyster Forklift Trucks Equipped with Heavy Duty Vista Masts [2]

Forklifts are produced by hundreds of companies all over the world. According to the data about lift truck sales, acquired by Worldwide Industrial Truck Statistics organization, Europe, North America, Japan and China are some of the biggest players in the market [3]. Toyota
Industries Corporation is No. 1 among all the industrial lift truck suppliers. It has 11 categories of forklifts, from hand pallet trucks to counterbalanced trucks, from electronic to engine powered, including more than 50 different types of forklifts. Each one of them can be ordered with different capacity and loading range to meet different needs. The loading capacity is from 0.75 ~ 8.5t. The maximum lifting height can be up to 14.8 meter [4].

Right now, all forklifts’ forks are attached to the truck on one end, and the lifting system use chain or cable. We feel like there are some improvements can be done, and we will focus on these two features in the rest of the research.

1.2 Proposed and Scope of Research Objectives

In this research, we investigate a forklift design that is new and different from existing designs. The new design offers two features: one is that the forklift is attached to the truck body on both ends, and the other feature is that the new lifting mechanism is more compact. The remainder of the thesis elaborates these new features in more details.

To achieve our new design goals, we need to do some research about the forklift existing design and what kind of product transportation is using
the forklifts. Based on that research, we need to find what the shortcomings of existing designs are. The new design offers both new and improvised features, over what is currently available. Next, we would use CAD modeling to create the new 3D design. Last, we would run analysis and calculation on the model to make sure it is stable and safe under working conditions.

1.3 Basic Systems of a Forklift

Usually a fully functional forklift would consist of the following major systems: the power system, driving system, loading system (including hydraulic transmission, lifting system, etc.). Our design here is more concerned with the loading system. Since we are not going to focus on the power, driving and control system, we will give a basic introduction in the following two sections (the power system will be included in the driving system).

1.3.1 Driving System

Like most of the trucks, one of the most important systems in a forklift is the driving system which allows the truck to move around. A steering system is one of the major subsystems for the driving operation. It rotates the front wheel to the desired direction set by the driver’s steering input. The direction is controlled by the steering wheel and the whole
movement is powered by a battery located in the back of the truck.

**Powering:** When power steering is used, pumps supply hydraulic pressure to power steering cylinders in order to make steering easier for forklifts with heavy loads. Electric power steering mechanisms replace the pumps and hydraulic fluid with motors when the wheel is turned.

**Steering Mechanism:** The purpose of a steering mechanism is to point the vehicle in the right direction. It is achieved through gears, tie rods, cables and a series of linkages. Currently, most lift trucks are front-wheel drive and they use the rear wheels for steering. All of the weight (including battery) is placed on the drive axle for traction and braking action (it is called counterweight). When the truck turns, the rear end swings while the front end is stationary. The wheelbase of the truck also affects the steering: the shorter the wheelbase, the easier to turn.

The steering system of a forklift consists of three major parts: a steering wheel connected to a steering box through a system of gears; linkages such as cables connecting the steering box to the front wheel assemblies; and front suspension parts such as tie rods which pivot the wheel assemblies.

A very special type of forklift uses Mecanum wheels [5] for omnidirectional steering as show in Figure 1.3. It allows the operator to
steer the truck forward, backward, diagonally and sideways, which also means this special wheel (See Figure 1.4) enables the truck to rotate 360° within its own footprint.

![Figure 1.3 Omnidirectional forklift [5]](image1.png)

![Figure 1.4 3-D Model Mecanum Wheel [6]](image2.png)

Like all those forklift systems, the truck's steering system requires regular maintenance and periodic replacement of parts, especially smaller parts like bushings and seals.

1.3.2 Power Steering (Control) System

During the driving operation, when the front wheels are steered, there
will be a restoring torque which tends to return the wheels to the original position. Though this restoring torque provides steering stability, the driver must provide sufficient torque to overcome this torque to steer the vehicle. That is why many forklift drivers have chronic back injury and pain due to the extra effort to maintain the stability of the truck. Since vehicles with heavy loadings require more steering effort, especially at low speeds, power steering was introduced to assist the driver. Most power steering systems consist of an engine-driven hydraulic pump and a hydraulic actuator [7].

Electric power steering (EPS) system uses an engine-independent motor for power steering, so it eliminates the need for complex hydraulic units. As a result, it provides power steering even when the engine is not working. With these advantages, EPS systems have begun replacing hydraulic power steering (HPS) systems in most of advanced forklifts and are expected to extend to all types in the future.

An EPS system has the following two functions. First, it can reduce steering torque. When a proper assist torque from an EPS system is applied in the same direction as the driver’s steering direction, the amount of steering torque required by the driver is relieved. Second, the EPS system can improve the return-to-center performance of the truck. It can
also eliminate excessive overshoot and subsequent oscillation by providing active damping capability and thus enhance return-to-center performance.

The typical control system of many EPS devices is shown in Figure 1.5. The target current setting unit determines the reference current $i_r$ to the motor based on current driving condition, and the controller calculates the control signal which minimizes the error between $i_r$ and the actual current $i_a$.

![Figure 1.5 Block Diagram of Typical EPS Control System](image)

The EPS system shown in Figure 1.5 uses what is called column-type EPS system, in which the assist motor connects to the steering shaft.
through spur gears and delivers assist torque to the shaft. Figure 1.6 shows the mechanical model of EPS devices. The load motor provides the emulated load torque including the one due to the friction between the tire and the road surface. These motors are all controlled by motor drives that receive input signals from the onboard computer in which the control logic is implanted.
Chapter 2 Review of Existing Forklift Trucks

Forklifts (also called lift trucks or fork trucks) are primarily used for lifting and transferring heavy loads to stations or locations in warehouses, shops or construction sites. Usually there are two forks in the front of a forklift (some type of forklifts have the forks on the side) that are used to lift loads that may weigh up to thousands of pounds. These forks can be moved forward and backward, and also up and down for lifting and moving cargo.

2.1 Introduction

A forklift truck is a powered industrial truck used to lift and transport materials. The earliest forklift truck was invented between 1914 and 1915 and put on the market since 1930s. After that, the increasing need of transporting military material during the World War II spurred the development of the Forklifts [9]. Following the war, more efficient methods for storing products in warehouses were being implemented. Warehouses needed more maneuverable forklift trucks that could reach greater heights. More new forklift models were made that filled this need. Since then, forklift trucks have become indispensable equipment in manufacturing and warehousing operations. In 2011, the size of the forklift manufacturing industry was nearly $27 billion [10].
2.2 Types of Forklifts

Forklifts come in a variety of sizes, configurations and weight-lifting capacities. There are a few different classes of forklifts that can be distinguished by two major features: their power sources and their configurations.

- Class 1: In terms of power sources, there are electric-powered forklifts and gas-powered ones.
- Class 2: In terms of configuration, there are counterbalance forklifts (four-wheel and three wheel), reach truck, order picker, multidirectional forklifts, side-loaders and some other types designed for specific needs.

2.2.1 Classification by Power Sources

Electric forklifts are powered by stored batteries and require frequent charging to operate. These forklifts are best suited for indoor use in areas where ventilation is not great because they are quiet and do not exhaust. Electric forklifts have lower operating costs than gas-powered ones. However, their lifting capacity is only 10,000 to 15,000 pounds. Their batteries can take as long as 16 hours to charge and cool off, and have a slower acceleration than those trucks that run on gas.

Gas-powered forklifts usually run on gas, liquid propane, diesel or CNG (compressed natural gas) and they are typically used outdoors due to
exhaust gases. They cost less than electric forklifts to buy, but they have higher ongoing costs, as they need frequent refueling. Gas-powered forklifts are typically capable of lifting weights ranging from 15,000 pounds to 35,000 pounds, which makes them ideal for heavy-industry situations and under in all types of weather [11, 12].

2.2.2 Classification by Configuration

Counterbalance Forklifts are the most common type of forklift truck. As the name suggests, counterbalance trucks use a counterbalance weight design, with a weight at the rear of the truck offsetting the load to be lifted at the front, as shown in Figure 2.1.

![Counterbalance Forklift](image)

Figure 2.1 Counterbalance Forklift [13]

Counterbalance machines are available as electric, gas or diesel powered. Electric counterbalance machines are able to operate with a smaller counterweight as the battery serves as a ballast as well as a source of power. On counterbalance trucks, the forks protrude from the front of the
machine, with no outrigging legs or arms. This means that no reach facility is required, and the fork lends itself to straightforward operation.

3-wheel counterbalance forklifts work the same way as regular counterbalance machines, however the inclusion of a single drive wheel in the center of the rear of the machine ensures maximum maneuverability as shown in Figure 2.2. They are perfect for use in applications where space is limited due to their tight turning circles and excellent maneuverability. They are also ideally suited for applications that require inside and outside use and racking loading [14].

![3-wheel Counterbalance Forklift](image)

**Figure 2.2 3-wheel Counterbalance Forklift [13]**

Reach trucks are designed predominantly for warehouse operations. They offer maximum lift height with excellent maneuverability as shown in Figure 2.3. They have the ability to ‘reach’ out beyond the stabilizing legs and therefore ‘reach’ into racking. The combination of this reach capability and the stabilizing legs means reach trucks can lift to great
heights (in excess of 10 meters) while still operating in very tight working environments. The stabilizing legs and batteries within a reach truck negate the need for any counterbalance weight within the truck construct. While excellent for use indoors, reach trucks are not ideally suited to work outside. Their low under-carriage clearance can cause problems on uneven working surfaces, and their electric power systems can be prone to contact trouble if regularly shaken due to undulating working surfaces.

Order picker forklifts have a platform which allows the operator to be raised with the picker. Order picker forklifts can carry large bulky items in tight spaces, and has room for picking product in addition to the operator’s standing. Figure 2.4 shows an order picker forklift.
Multidirectional (four-way) Forklifts usually have a driving wheel at one side, and two wheels on the other side as shown in Figure 2.5. This type of forklift has more flexibility and efficiency in warehouses, they can save more time and space to increase productivity.
Side-loaders usually have large pneumatic wheels and a stable platform for long loads to rest on and they can quickly transport long material through narrow gates and aisles in lengthwise drive as show in Figure 2.6. They are designed to carry loads lengthwise in the direction of travel enabling transport through what would otherwise be too small of a door opening [17].

There are also forklifts that come in varied sizes. One of these is the narrow-aisle forklift, a standard electric forklift designed to function in small areas. These are narrower than standard forklifts, and often have additional features like the ability to move the forks without moving the entire forklift or a cab that rises with the forks to improve driver visibility.

Other forklift types include rough terrain forklifts, which are gas-powered
forklifts designed for rough conditions. They are larger, with off-road wheels and four-wheel drive functions to get them through mud, grass and other outdoor terrain [18].

Motorized pallet trucks are also known as walkies, riders or walkie riders. These vehicles derive their names from the fact that the operator does not have to sit inside the vehicle to operate it. In fact, he walks along the side of the truck as it moves the load.

Swing mast trucks are vehicles that typically used in a narrow aisle. They are similar in appearance to standard trucks. However, their masts can swing up to 90 degrees in one direction only.

Turret trucks are also used in very narrow aisles. Like the order selector, they can lift both the load as well as the operator. However, in addition to that, turret trucks can swing the forks 90 degrees on either side (which means 180 degrees total).

2.3 Advantage and Disadvantage of Existing Design

In a warehouse, space is a very important issue to be taken into account. The less space required for aisles, the more space that will be available for storage or other needs. For this reason, narrow aisle forklift was developed. These narrow aisle forklifts can operate with minimal aisle space.
These units designed for narrow aisles have special attachments which allow them to stock and retrieve material with very little turning or maneuvering room, but they still need to face the shelves and move forward to carry the loads. And most of these units require the operator to stand upright while operating the machine.

Right now, most of the forklifts are using counter weights to balance the weight of the cargo. They have two forks (also known as blades) in the front that are used to lift loads. These steel blades can be moved forward and backward (with the truck), and also up and down for lifting and moving cargo. The distance between the blades can be adjusted according to the size of the weight that needs to be lifted.

The other important issue in a warehouse is how to fully use the vertical space when it comes to storage. Right now, most of the forklifts can only pick up loads as high as their forks can go; not so many forklifts can reach higher to store/pick up cargo stored in a higher shelf. There are some forklifts using roped transmission system to move the operator cabin up and down, but it can be very unstable when the truck takes the heavy loads.

2.4 Thesis Research

As the literature research covered in this chapter indicates, narrow aisle
forklifts have their limitation in rotation. Our research will focus on design, analysis and simulation of a fork mechanism that rotates 180 degrees, attached to truck body on both ends, with a scissor lift under the operator’s cabin, which increases the working height. The research will also study the stability of the truck to prevent its tipping over.

Our research truck model is based on counter balance narrow aisle forklift. The basic idea is that, in order to save the aisle space for truck to move or turn, the forks of the truck would be designed to be able to rotate and face either direction of the aisle. In this way, a forklift can drive into a very narrow aisle and turn the forks aside to lift cargo without turning the entire truck. And with the scissor lift under the operator cabin, the forks can pick up higher load, thus the vertical space of a warehouse will be fully used.

The following chapters will focus on creating a new design of the fork based on the existing forklift type with certain criteria, creating a CAD model of the new design, doing stability calculation to prevent the tipping problem and performing force/stress analysis on the new design.
Chapter 3 Design Synthesis

3.1 Design Criteria

When it comes to the design of a forklift, there are a few things that need to be fully understood first, like the basic components of forklifts, what kind of power source we are going to use, how the loading device works, what is the truck’s capacity, etc. Those things are the foundation of a forklift design and need to be decided first, and then we can move on to other details, like the dimension of each component and choosing the right wheels. In this chapter, we are going to go over some basic design criteria to get an overall idea about the design of the whole truck.

3.1.1 Basic Components

First we are going to discuss is the basic structure of our forklift.

*Truck Frame:* this is the base of a forklift to which the loading device, counterweight, power source and wheels are all attached. The frame may already have the fuel and hydraulic tanks constructed as part of the frame assembly.

*Loading Device:* this part includes the mast, carriage, lifting chain, and forks, as shown in Figure 3.1. The mast is the vertical assembly that does the raising and lowering load. It is hydraulically driven, and operated by one or more hydraulic cylinders. It will be mounted in front of the frame
of the forklift in our design. The carriage is the component to which the forks or other attachments mount. It is mounted into the mast rails by chains or directly attached to the hydraulic cylinder and it does move up and down. The lifting chain links the mast and carriage together. Forks are the parts that have direct contact with the cargo when operating.

![Figure 3.1 Different Parts of Forklift Loading Device](image)

**Counterweight:** this is the mass attached to the rear of a forklift truck frame. The purpose of the counterweight is to counterbalance the load being lifted. When a forklift is electric driven, the large lead-acid battery itself could be count as part of the counterweight.

**Power Source:** one of the main options is an internal combustion engine that can be powered by LP gas, CNG gas, and gasoline or diesel fuel. The other option is electric forklift which is powered by either a battery or fuel cells that provide power to the electric motors. The electric motors used on a forklift can be either DC or AC types. We choose electric
battery for our forklift, and the battery would sever as part of the counterweight.

**Tires:** the tire type depends on different working ground conditions. If the forklift mostly works indoor, then we should choose solid tires; if it is for outdoor use, the pneumatic type would be better. Our truck is used indoor, so the solid tires would be our choice.

**Cabin:** this is the part where the operator would sit inside and do the driving and loading. It contains a seat for the operator along with the control pedals, steering wheel, levers, switches and a dashboard containing operator readouts. The cabin area could be either open air or enclosed, but it must be covered by overhead guard to ensure the operator’s safety.

**Overhead Guard:** this part is usually a metal roof supported by posts at each corner of the cabin that protect the operator from any falling objects, so it is very important. It could be a separate assembly or in some forklifts, the overhead guard is an integrated part of the truck frame assembly.

**Attachments:** when it comes to attachments for a forklift, various types of material handling attachments are available. We will need to change or add those special attachments when dealing with different types of load. For example, if the loads are fragile and hard to stay put during the transportation, we might need to add a load stabilizer, see Figure 3.2. The
load stabilizer lightly clamps the load from above. It is highly useful for those fragile and individual loads that are not likely to remain in place during transport via the forklift.

![Load Stabilizer](image)

**Figure 3.2 Forklift with Load Stabilizer**

What we need to consider here is that, any attachment on a forklift will reduce its nominal load rating, which is computed with a stock fork carriage and forks. So when we use additional attachment, the actual load rating may become significantly lower.

Those are the main components of our forklift, more design details of them will be further discussed in Chapter 4.
3.1.2 Stability Triangle & Tipping over

The most important consideration when designing a forklift is the safety issue, while the truck is doing the loading and moving.

The forklift’s stability system consists of 3 points of contact: 2 front wheels and the center of the rear axle for a 4-wheel forklift, or the rear steer wheel on 3-wheel trucks. Without these 3 points of contact, the forklift could not even safely sit on an uneven ground.

![Figure 3.3 Center of Gravity Horizontal Shifting Illustration](image-url)
When a forklift lifts cargos, apparently its center of gravity would shift to the front wheel line due to the extra weight put on, see Figure 3.3, which will leads to our first problem, the stability of loading process. We need to make sure the truck would sit still without tipping forward.

A number of manufacturers included features to control the mast angle, especially with a raised load. For example, the Toyota Active Mast Function Controller senses and reacts to instability by restricting the mast angle and speed according to the load's height and weight. This feature assists in preventing forward tipping due to the reduction in lift capacity caused by the mast tilting function.

The second safety issue that we need to take care of is the side tipping over during forklift’s transportation. See figure 3.4. The stability of a forklift changes constantly due to the speed and turning rate of the forklift. Regarding this issue, there are actually two ways to prevent this problem.

![Forklift Side Tipping during Transportation](image)

Figure 3.4 Forklift Side Tipping during Transportation[19]
The first solution is introducing a new system called SAS - System of Active Stability. This system was first designed by engineers in Toyota Material Handling Company to reduce the likelihood of side tipping over. The system monitors key forklift operations, detecting instability through a series of sensors. When the computer senses instability, the Active Control Rear Stabilizer (a hydraulic cylinder with an electromagnetic fluid lock) locks the normally pivotal rear axle to help prevent lateral tipping-overs. Figure 3.5 shows how this stabilizer works during transportation.

![Figure 3.5 Demonstration of System of Active Stability (SAS) [19]](image)

The second method of preventing side tipping over is speed control. Speed is always a contributing factor to both collisions and stability-induced incidents, so speed limiting seems very necessary. As shown in Figure 3.6, due to a forklift’s high center of gravity, it is likely that overturning (lateral tipping-over) will occur when the forklift corners at high speed (Actually 75% of side tipping-overs occur even when the forklift is empty). When the mast is raised, the center of gravity becomes
higher and the risk of side tipping over increases. As to this problem, stability control systems that include speed controls and braking based upon load weight and the effective positioning of the combined center of gravity is being introduced into those forklifts. In our case of battery powered trucks, it is standard equipment.

Figure 3.6 Center of Gravity Vertical Shifting Illustration [20]

In the meantime, options are available to reduce speed without affecting material handling performance. There are systems available that can be set for various working conditions. For example, as the forklift passes a beam on the door it switches the speed controller to outdoor mode and allows unrestricted travel speed. When entering the building again, the beam triggers the speed controller to limit maximum speed to walking pace. That’s how those stability control system works.
Our focus is mainly on the stability of forklift during its loading period. We will be discussing more about the safety triangle and performing the stability analyses in Chapter 5. It is very important to make sure our design will be stable and the operators will be safe when the forklift is working.

### 3.1.3 Safety Issues

Apart from stability triangle & tipping over just discussed, this part of safety issue is mainly focused on the failure of forklift itself, including fracture, fatigue failure and other types of damage. Among all of those forklift failure cases, fatigue failure is the main reason.

Forklift trucks convey raw materials to the production line, scrap and final products to the storage areas or to the transportation trucks. The load support parts of forklift, those forks, are subjected to repetitive stress conditions of a variety of load and frequency spectra, including loading and unloading cycles and vibrations coming from moving on irregular terrain conditions. These cyclic loading takes place under normal operating conditions of various machine components, resulting in the action of fatigue failure mechanism [21, 22].

There are some other types of damage that can happen during the use of a forklift and some simple solutions to prevent them exist.
First, using the incorrect type of forklift in an application can cause premature wear and failure to major components. Also, operating with worn or incorrect lift truck tires would raise maintenance expense. When it comes worn tires, it is required to use the proper tires if we want the maximum forklift performance. In addition, forklifts are not equipped with suspension springs that provide additional cushioning like cars, so it is important to replace worn or chunked tires that cause jarring impacts to the wheel, as Figure 3.7 shows. Also, operating with worn tires can also cause premature wear to the bottom of the forks. This would jeopardize the forklift's ability to lift and creates an unsafe work environment. That is why The American National Standards Institute (ANSI) and Industrial Truck Standards Development (ITSDF) require replacing the tires when the heel is worn more than 10%.

Figure 3.7 Wheel Damage Caused by Worn Tires [23]

Second, although forklifts are designed to lift and carry heavy loads, a congested work area is another cause of impact damage to product, equipment or facilities. Pushing pallets can result in premature tire wear
and expensive transmission damage. All those major components such as tires, wheels, body panels, forks and backrests suffer when forklifts encounter impact to product and surroundings due to its high travel speeds. Impact monitor and vehicle speed limiters are available to help reduce impact damage.

The third problem is the floor conditions. Driving over debris such as wood, plastic wrap and banding can cause radiator or axle damage, and if those blown into the engine compartment, it can destroy the cooling system and potentially cause engine failure or a fire. So we should always keep the working condition clean.

In order to estimate the influence of the applied loads on the forklift, it becomes necessary to assess the strength of the forks. We will perform a full FEM/FEA analysis in Chapter 6 to ensure the safety of our forklift.
3.2 Existing Designs

After our discussion of those criteria about designing a forklift, before we start to design, we need to know what designs have already been in existence. We could use them as references and base our own innovation design on them.

3.2.1 Side-Loader

Figure 3.8 shows how a narrow aisle side-loading forklift works. Those electric Side-loading forklifts are extremely maneuverable and adapt easily to special demands. They usually have 4-directional capability, optional all wheel steer to handle long loads in narrow aisles [24].

Figure 3.8 A Narrow Aisle Side-loader
When using a side-loader, the operator doesn’t have to drive the forklift forward in order to move the fork and do the loading. The lifting and moving cargo process can be done merely by controlling the forks to move forward and backward. And that is exactly what we are using as one of our forks movements. When we make the forks rotatable, we could put those side-loading forks in front of the truck. Instead of facing the whole truck to the shelf every time before the lifting motion, the forks will do the side-loading motion, and rotate back to its own position.

3.2.2 Chain Transmission of the Operate Cabin

Figure 3.9 is an example of a forklift with a cable lifting system attached in the back of its forks. With this chain transmission, those forks are able to do the up-and-down lifting motion [25].

![Figure 3.9 Forklift with Cable Lifting System](image)
3.3 Different Design Ideas Proposed

With all the research we have done, three original design ideas are proposed here. These designs all have their own features, which include different rotation angles and lifting mechanism. We are going to introduce them one by one, compare their advantage & disadvantage and finalize our design.

3.3.1 Design 1: 360° Rotate Forks with Chain Lifting Transmission

First thing here we want to do is to increase the rotation angle of those forks, see Figure 3.10. The rotation of the forks can be 360 degree, and after the forks are loaded with cargo, they will rotate and rest on the top of the operator cabin, which saves time from coming all the way down to the lowest point.

![360 degree rotation](image)

(a) Starting Position                    (b) Ending Position

Figure 3.10 Forklift with 360 Degree Rotation Forks
The second feature this design has is the chain lifting transmission system for the operator cabin, see Figure 3.11.

As we discussed in 3.2.2, this chain transmission is very similar to the rope transmission we use in our elevators [26], see Figure 3.12. In roped elevators, the cabin is raised and lowered by traction steel ropes rather than pushed from below. The ropes are attached to the cabin, and looped around a sheave. The sheave is connected to an electric motor. When the motor turns one way, the sheave raises the cabin; when the motor turns the other way, the sheave lowers the cabin. Typically, the sheave, the motor and the control system are all housed in a machine room above the cabin. The ropes that lift the cabin are also connected to a counterweight, which hangs on the other side of the sheave.
Figure 3.12 Forklift with Cable System

The chain transmission used here is commonly seen among forklifts. But this design has a problem, which is that, the over-heading loading can be dangerous during the transportation. After picking up the load, the cargo would stay above the operator’s head the entire time. Although the cabin would be tested to make sure it is strong enough to support the loading, considering the roof failure accident might danger driver’s life, the safety issue of this design is still a concern to us.
3.3.2 Design 2: 180° Rotate Forks with Hydraulic Pump

In design 2 we use 180 degree rotation on forks. The cargo would always stay in front of the vehicle. Under the operator cabin, there is a hydraulic pump installed in order to lift the cabin along with those forks. Figure 3.13 shows how this hydraulic pumping system works. The hydraulic pump under the operator cabin will change the height of the cabin, so the forklift can pick up higher load.

(a) Starting Position                  (b) Ending Position

Figure 3.13 Hydraulic Pumping System Working Demonstrations

The motion of the forklift cabin is inspired and related to the motion of a hydraulic elevator [28], see Figure 3.14. This hydraulic system lifts the cabin using a hydraulic ram, a fluid-driven piston mounted inside a cylinder. The main advantage of hydraulic systems is they can easily
multiply the relatively weak force of the pump to generate the stronger force needed to lift the cabin and the cargo.

![Figure 3.14 Demonstration of a Hydraulic Elevator](image)

This system is incredibly simple and highly effective, but it does have some drawbacks. The main problem is the size of the equipment. In order for the cabin to reach certain height, we have to make the piston long. The cylinder has to be a little bit longer than the piston. Higher loading range means longer cylinder. Since the entire cylinder structure must be buried below the bottom cabin which means we have to build the operator cabin higher. We already talked about the shifting weight center of a forklift. High operator cabin also means higher center of gravity which leads to the risk of tipping over, and we don’t want to see that kind of accident.
3.3.3 Design 3: 180° Rotate Forks with Scissor Lift

The idea in design 3 is that we use a scissor lift instead of hydraulic pump to achieve the vertical movement of the operator cabin of the forklift. Figure 3.15 shows how a scissor lift truck looks like under working condition (left) and resting conditions (right). As we can see, after the scissor lift finish its job, it can be compressed to a very compact shape which would save space and we don’t need to build the operator cabin high. Normal cabin height means low center of gravity so the whole vehicle would be more stable.

![Figure 3.15 A Scissor Lift Truck’s Working Condition](image-url)

(a) Extended Position  
(b) Resting Position
The power behind the scissor lift is also hydraulic. The difference between scissor lift and elevator system is how the hydraulic pump behind them works. The pump serving the hydraulic elevator is working vertical while the one serving the scissor lift is working with an angle and the angle is changing constantly along with the height of the whole system. As shown in Figure 3.16, there is one very powerful hydraulic pump inside of the scissor lift structure to change the height as operator’s wish.

Figure 3.16 Hydraulic System of a Forklift

Figure 3.17 is the 3-D scissor lift model we are going to use in our design. Unlike the one in Figure 1.16 that has multiple layers, our model has only one layer. Since our forklift will work inside a warehouse which will have a height limit, one-layer scissor lift is enough for that.
This design has a 180 degree rotation angle to ensure that this forklift can pick up loading from both sides of the aisle. With two hydraulic pumps inside, our scissor would have enough power to hold up both the weight of the operator cabin and the cargo load combined together.

3.3.4 Summary of Design Ideas

Table 3.1 shows the difference between each design idea. Each feature is graded on a scale of 1 star to 5 stars to give a more clear idea.

Table 3.1 Comparison of Forklift Design Ideas

<table>
<thead>
<tr>
<th></th>
<th>Design 1</th>
<th>Design 2</th>
<th>Design 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation angle</td>
<td>360</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>Cabin lift mechanism</td>
<td>Chain</td>
<td>Hydraulic Pump</td>
<td>Scissor Lift</td>
</tr>
<tr>
<td>Flexibility with different cargo &amp; change of attachment</td>
<td>★</td>
<td>★★★★★</td>
<td>★★★★★</td>
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<tr>
<td>Loading height range</td>
<td>★★★★★</td>
<td>★★</td>
<td>★★★★★</td>
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<tr>
<td>Loading &amp; transportation efficiency</td>
<td>★★★★★</td>
<td>★★★☆</td>
<td>★★★☆</td>
</tr>
<tr>
<td>Vehicle stability</td>
<td>★</td>
<td>★★★☆</td>
<td>★★★★★</td>
</tr>
</tbody>
</table>
Design 1: 12 stars
This design has a $360^\circ$ rotate forks with chain lifting transmission for the operator cabin. It has a full loading range and saves time from keeping the forks half way down during the loading which increase the efficiency of the loading process.
But, due to the $360^\circ$ rotation of forks resting on top of the cabin, this design cannot be easily adapted to other loading device or using other attachments. And the risk of cargo breaking the roof of the operator cabin is high and the high center of gravity during transportation would also be dangerous. So the biggest problem of this design is the safety issue.

Design 2: 15 stars
This design has a $180^\circ$ rotate forks with hydraulic pump. The forks can be easily changed to other types of attachment. Because of the hydraulic pump under the operator cabin, the stability of the vehicle is good.
But, due to the inevitable pump height, the operator cabin would be built high which lead to a high center of gravity and it inhibits the loading range (the forks cannot go all the way down to pick up the lowest cargo).

Design 3: 19 stars
This design has a $180^\circ$ rotate forks with scissor lift. In design 3, forks can be easily changed to other attachment. It has a full loading range. The
vehicle is stable with the support of the scissor lift. Its efficiency may not be as good as design 1, but it has a great overall performance.

After comparing, all three ideas, we decide to go with design 3. It has the highest score and overall is the most stable and safest design.

### 3.4 Final Design Schematic

After summarize all these criteria above and our proposed design ideas, Figure 3.18 is the draft of Design 3 forklift.

![3-wheel Electrical Powered Forklift Draft](image)

Figure 3.18 3-wheel Electrical Powered Forklift Draft

It is a man-operated, electrical powered, 3-wheel forklift with a scissor lift elevating mechanism under the operator cabin and a hydraulic system to ensure a 180 degree loading range. This is our final design.
Chapter 4 Modeling of Forklift Design

Since we have decided the final design and did the hand draft in Chapter 3, the next step is to create the 3D CAD model. Here in Chapter 4 we use computational methods (Solidworks) to achieve this goal. First, we will create all parts with proper dimensions that needed in our design, then we will assemble some of them as subassembly and put them with the rest altogether as an entire assembly.

4.1 Introduction

In our design, a total number of 37 parts have been designed and created individually. Among these components, 14 of them are put together as a subassembly named Scissor Lift and 10 of them as another Lifting Fork subassembly. Our final forklift assembly model here composed of these two subassemblies along with the remaining 13 parts (including the truck chassis, counterweight, mast, cargo, etc.).

In section 4.2, first, we introduce the scissor lift subassembly with a brief description of each individual component that makes it. Second, the exploded views will help understand how those parts are assembled together. Each part uses features like extrusion, sweep, revolve, extruded cut, shell, fillet, and holes. Then we introduce each single part using isometric view and its dimensions with different views (front, top, bottom,
etc.) of engineering drawing. Since the scissor lift is the important lifting device of operator cabin, its mechanism will be introduced at the end of this section as well.

In section 4.3 we basically introduce the subassembly of lifting fork and its parts the same way as in section 4.2. Lifting fork system has direct contact with the cargo and is responsible for the loading process, so it is important to understand those forks’ movement when they pick up the loads and how they act during resting & transportation.

In section 4.4, we introduce all the remaining parts. Their features and detailed dimensions are presented using isometric view and engineering drawing.

In section 4.5, the final rendering model of our forklift is presented. We also give a full description of how the final assembly model is created using its collapsed and exploded view.
4.2 Scissor Lift

The scissor lift is the lifting system that is placed under the operator’s cabin. It functions as a lifting device, changing the height of operator’s cabin to provide a clearer operating view. Since forks are connected to the operator cabin, the rise of the cabin will also deliver a higher loading range.

4.2.1 Scissor Lift Assembly

Figure 4.1 Collapsed View of Scissor Lift Assembly

Figure 4.1 is the collapsed view of the scissor lift assembly used in our forklift design. The feature tree listed on the left consists of 14 components. The top case and base case are supported by two frames which are connected by two hydraulic pumps. There are two wheels for
each frame, so they could move along the designed path inside both cases.

Figure 4.2 is the exploded view of the scissor lift assembly. Each component is displayed in the pre-assembled position to help understand how the subassembly is assembled in 3-D. These two hydraulic pumps as shown are connecting Frame 1 and Frame 2 together and they also change the distance between the top and bottom cases. Both frames are fixed to one case on one end and connecting to the other case by its wheels.

Some of the parts used here are the same, e.g. wheels and two identical pumps (which including a pump case, pump hinge and piston). Overall there are 8 different components designed here. Figure 4.3 – Figure 4.8
are the isometric view and engineering drawings of each of these individual parts. All parts’ dimensions are introduced here as well.

Figure 4.3 – Figure 4.7 are the isometric views and dimensions of all the components designed for this subassembly.

Figure 4.3 Overview & Dimension of the Base (cm)
Figure 4.4 Overview & Dimension of the Top (cm)

Figure 4.3 & 4.4 are figures of the top and bottom views of the case. They basically have the same outline dimensions. The difference is the inside structure. These two cases are connected by frames and their wheels. Due to the thickened material, we need two rails with different width to allow those wheels to pass.
Figure 4.5 Overview & Dimension of the Frame 1 (cm)
Figure 4.6 Overview & Dimension of the Frame 2 (cm)

Figure 4.7 Overview & Dimension of the Wheel (cm)
4.2.2 Working Mechanism

Figure 4.8 shows how the scissor lift is placed above the truck chassis with the operator cabin on top of it. Here in Figure 4.8a shows, the scissor lift in its collapsed configuration position when the hydraulic pump is not working. Figure 4.8b shows how it is under working condition. The hydraulic pump is extended pushing frame 2 up and raising the top case at the same time.

(a) Collapsed Configuration                (b) Expended Configuration
Figure 4.8 Scissor Lift Supporting Operator Cabin

(a) Collapsed Configuration                (b) Expended Configuration
Figure 4.9 Hydraulic Pump
Figure 4.10 shows the front view of the scissor in the assembly drawing. Using Solidworks measurement tool shows that the distance between the top and bottom case of our scissor lift is 1.26 m. Since this is the scissor lift maximum position, 1.26m is the maximum loading.
4.3 Lifting Fork

The lifting fork is one of the most important parts of the forklift. Its job is to grab the load from shelves and move it up and down during the loading process. It is placed in front of the whole truck and connected to the operator cabin. First we will introduce the subassembly and its components. Then we will demonstrate how lifting fork work by demonstrating its three basic movements.

4.3.1 Lifting Assembly

![Collapsed View of Lifting Fork Assembly](image)

Figure 4.11 Collapsed View of Lifting Fork Assembly

Figure 4.11 is the collapsed view of the lifting fork assembly used in our forklift design. As the feature tree listed on the left shows, the assembly consists of 10 parts. There are two forks installed in front of the support
frame and the support frame is attached to the fork lid through a pillar which is rotatable to provide the lifting fork system with a rotation movement. There are two axles connecting the fork support frame with its two motors and rack fixer. One motor lifts the fork lid and the other one (rack motor) moves the whole system horizontally. We will discuss these three motions in detail in the next section. The down rack fixer connects the fork lid with operator cabin, to make sure the entire system is stable in front of the truck.

Figure 4.12 following is the exploded view of the lifting fork assembly. Each component is displayed in the pre-assembled position to help understand how the subassembly is assembled in 3-D.
Overall there are 9 different components designed here. Figure 4.13 – Figure 4.19 are the isometric view and engineering drawings of 7 of them. The motor used here is a standard part, not designed specifically. All parts’ dimensions are introduced here as well.

Figure 4.13 Overview & Dimension of Fork Lid (cm)
Figure 4.14 Overview & Dimension of Fork Support Frame (cm)
Figure 4.15 Overview & Dimension of Rack Axle (cm)

Figure 4.16 Overview & Dimension of Rack Fixer (cm)
Figure 4.17 Overview & Dimension of the Fork (cm)
Figure 4.18 Overview & Dimension of Spur Gear (cm)

Figure 4.19 Overview & Dimension of Rack Motor (cm)
4.3.2 Loading Movement

Movements of lifting fork can be simplified as three basic motions: horizontal, vertical and rotation. Here we will use the lifting fork assembly and the cabin to demonstrate them.

First, the forks are at resting position as in Figure 4.20a shows. The forks usually rest on one side of the truck (depending on which side of aisle the load is sitting and the fork will be on the other side waiting for the next move). In this case it is on the left side of the truck. After the forklift reaches the cargo, the forks will move forward in order to go under the cargo, as Figure 4.20b shows. The arrow indicates the forks move to the right of the truck.

![Fork Horizontal Movement of the Forks](image)

(a) Starting Position  (b) Ending Position

Figure 4.20 Fork Horizontal Movement of the Forks

When those forks reach under the cargo, part of the fork assembly, including forks, the support frame and fork lid, will move up to lift the load up, see Figure 4.21.
After the load is picked up, the forks will retreat to its middle position as shown in Figure 4.22a. At this point, the cargo has completely been moved away from the shelf and resting on those forks. Then the fork support frame makes a 90° turn to make the cargo face in front as in Figure 4.22b. This is to make sure the whole center of gravity remains in the central line after adding the load and the truck keeps balance during the transportation. Then the forklift drives off the aisle and heads to its destination.

Figure 4.21 Vertical Movement of the Forks

Figure 4.22 Rotation of the Forks
4.4 Other Components

After introducing two subassemblies (Scissor Lift and Lifting Fork), there are still some additional components. In this section, drawings and dimension of those parts are shown in Figure 4.23–Figure 4.31.

Figure 4.23 is the operator cabin. It is the control center of the forklift on top of the scissor lift system. Those bars above the operator act as a protection.
Figure 4.24 Overview & Dimension of Truck Seat (cm)

Figure 4.25 Overview & Dimension of the Steering Wheel (cm)
Figure 4.24 & 4.25 are the seat and steering wheel that are placed inside of the operator cabin. They allow the driver to control the movement of the forklift.

Figure 4.26 is the chassis of the forklift. It is the base of the truck holding every component together. The scissor lift system is placed on top of it.

(a) Isometric View

(b) Top View

(c) Right View

Figure 4.26 Overview & Dimension of Chassis (cm)
Figure 4.27 Overview & Dimension of Counterweight (cm)
Figure 4.28 Overview & Dimension of Mast 1 (cm)

Figure 4.27 is the counterweight of the forklift. It includes the battery and the motor that driving the whole truck. The counterweight keeps the entire forklift in balance.

Figure 4.28 and Figure 4.29 are the Mast the behind the scissor lift and
the operator cabin. These two components assembled together would function as a support for the scissor lift and keep the movement of the lift only to vertical.

Figure 4.30 is the front and back tires. The designs are the same; dimensions are the difference between these two tires.

(a) Isometric View

(b) Font View

(c) Top View

Figure 4.29 Overview & Dimension of Mast 2 (cm)
Figure 4.30 Overview & Dimension of Tire (cm)
4.5 Assembly Model

After introducing all the components and subassemblies in our forklift design, it is time to see the entire design. Figure 4.31 is the rendering model of the forklift truck collapsed view. This generates a more realistic image about how the forklift looks under its working condition.

Figure 4.31 Rendering Model of the Forklift

Figure 4.32 shows Figure 4.31 with the feature tree. As the feature tree shows on the left, there are 12 components (not including cargo) and two subassemblies. We have already introduced both subassemblies in previous section. The scissor lift pushes up the operator cabin alone with the lifting fork and the lifting fork in front of the truck is what the driver controls to pick up and drop all loads.
Figure 4.32 Collapsed View of Forklift

Figure 4.33 is the exploded view if the forklift. It separates the forklift into 6 different major parts: the lifting fork in the front, the scissor lift, the operator cabin above it and the chassis under it, the supporting mast and the counterweight.

The chassis is at the bottom, on top of it are scissor lift and operator cabin. The lifting fork system will be connected to operator cabin with its motors and the down rack fixer. They allow the system to move under the driver’s control. During the loading process, the center of gravity will shift left or right, if the load is very heavy in which case it might cause the failure of the scissor lift. For safety first, we add a supporting mast behind the cabin to disperse some of the stress from the scissor lift. In this way, the scissor lift will not need to take all the force by itself. This is a
very useful safety control. Also a counterweight region is placed behind the entire forklift. The battery is inside of the counterweight so there is no need to make room especially for it. It serves as part of the weight to keep the truck balanced.

Figure 4.33 Exploded View of Forklift
Chapter 5 Stability Analysis

We have presented the forklift CAD design and model including all its individual parts and subassemblies in Chapter 4. In this chapter we use analysis tools to ensure that the forklift meets the safety requirements of its operations. Mass property calculations tool is used here. This application gives us the volume, mass, center of mass, principal moments, axes of inertia and other properties of the model we need. We also perform those measurements to ensure the stability of our forklift under resting and loading conditions.

5.1 Mass Properties Calculations

Before using the CAD/CAM system to calculate the mass properties of our model, we need to assign material properties to every individual component. Each part would use a different material when manufactured due to its own function in the entire system. After that, we calculate the mass and center of gravity of the forklift. Finally we perform FEM/FEA.

5.1.1 Mass Properties of Components, Subassemblies & Assembly

Figure 5.1 – Figure 5.7 is the mass calculations of all the components, subassemblies & assembly after being assigned a material.

Figure 5.1 shows the overall weight of the fork body (including the chassis, tires and the counterweight). Scissor lift, counterweight and tires
are directly attached to chassis; it’s the base of the entire truck.

Counterweight is also a very important component of the forklift. It is the part that makes sure the forklift can maintain its balance while working. As Figure 5.2 shows, the mass property of the counterweight is 1500kg. This forklift is driven by electric; the battery is installed inside of the counterweight as part of the counterweight. This is the reason that in the zoom-in picture it shows over-ridden. We add the weight of the electric battery in it.
Figure 5.2 Mass Property of Counterweight

Figure 5.3 Mass Property of Operator Cabin

Figure 5.3 is the mass property of the operator cabin, which includes the cabin, the steering wheel and the seat. The overall weight is around 400kg. The overhead structure is very important because if it fails during the loading, operator’s life will be in danger. To ensure that situation will not happen, we will do a full stress analysis of the overhead structure.
Figure 5.4 is the mass property of the supporting mast which includes both frames. The frame’s job is to make sure the operator cabin is stable during its up-down movement.

Figure 5.5 Mass Property of Subassembly: Lifting Fork
Figure 5.5 & Figure 5.6 show the mass properties of two subassemblies: Lifting Fork and Scissor Lift. The lifting fork needs to be strong enough to support the load. As for the scissor lift, not only the load needs to be supported, it also needs to take the weight of the cabin and the entire lifting fork system.
Figure 5.7 shows the overall weight of the forklift assembly. It is about 4458kg. Usually a forklift works at an indoor warehouse. There is a certain amount of weight a ground can take. Wearing the ground would cause some uneven road. During the transportation, those roads would make the transportation bumpy, and it would cause sudden load on different part of the truck. Those sudden loads may cause truck failure. That is why the weight of the forklift matters. In our case, most warehouse floor could take a truck with such weight.

5.1.2 Center of Gravity under Static Condition

Since we already have the data about the mass properties of all the components, we need to investigate if the forklift is safe under static conditions. This entails that forklift center of gravity needs to stay within the safety triangle, as shown in Figure 5.8; otherwise the forklift will tip over (see section 3.1.2).
Figure 5.9 & Figure 5.10 shows clearly that when the forklift is under static condition, the center of gravity of the tuck remains in the safety triangle zone.

The arrow in Figure 5.9 indicates that, when forks move up and down, the mass center also moves up and down, but it will still remain in the safety area.

The arrow in Figure 5.10 indicates that, when forks move left and right, the mass center will also move to the left or right. Since this is a symmetric design, if the forklift can remain stable when forks are on one
side (like shown in Figure 5.10, forklift is stable when the forks are on the right side), then it will also be safe when fork move to the other side.

5.2 Stability of the Forklift

Section 5.1 discussed our forklift under its static condition. In this section we discuss the safety issue of the truck as well, but here we focus on truck’s performance under its working (loading) condition. First we discuss what would happen if we change the shape of the safety triangle. And then we use the measurement tool in Solidworks to calculate the maximum loading capacity of our forklift.

5.2.1 Safety Triangle Adjustment

Stability triangle is defined as the area that is inside of two front wheels and the pivot point of the rear axle. The dimension of our forklift’s stability triangle is shown in Figure 5.11. It is an isosceles triangle with a 1.5m bottom and two 2.7m sides.

Figure 5.11 Top View of Forklift with Stability Triangle Dimension
If we need to change the dimension of the safety triangle as shown in Figure 5.12 from ① to ②, what we need to do is make the distance between two front wheels wider and shorten the auto body length at the same time. Such a change is safe as long as the truck center of mass is remained within triangle ②.

Figure 5.12 Adjusted Stability Triangles

Since we are designing a narrow aisle forklift here, which means the distance between two wheels cannot be too wide, otherwise the vehicle will have problem driving through those narrow aisles to pick up the loads. Based on that condition, we set the distance between those two front wheels as 1.5m. As to the body length of the forklift, we want the truck to be able to turn in a very small area, so the body length of the truck cannot be too long, while at the same time, we want to make sure the stability triangle will be big enough to maintain balance during the loading and transportation process. After a full consideration including mobile ability, safety and battery size, setting the body length of the
forklift as 2.7m seems to be most reasonable.

5.2.2 Maximum Loading Capacity Calculation

After we determine the stability triangle of the forklift, we need to calculate the loading carrying capacity of the truck. We already know that the truck’s center of mass needs to be inside of the safety zone; otherwise the truck will tip over and cause serious accidents. In this section we are going to calculate the maximum loading result with the help of mass calculation tool.

First, as Figure 5.13 shows, we put on a heavy load on these forks to see what would happen to the truck’s mass center. Here we use a cargo weight of 3000kg to do our calculations.

![Forklift with 3000kg load](image)

Figure 5.13 Forklift with 3000kg load
And then we do a whole assembly mass calculation to the forklift, the result is shown in Figure 5.14. It shows where the mass center is located now.

As we can see from Figure 5.14, the mass center of the truck is out of the safety zone (between two black lines), which means under this loading condition, the forklift is not safe. Apparently, the 3000kg weight load is
too much for our forklift, so we need to adjust the load we apply. After we change the weight of load a few times (2800kg, 2500kg, 2300kg and 2100kg), finally when the load comes down to 2000kg, as shown in Figure 5.15, we get the result we want: the mass center position stays inside the safety zone.

The result of mass calculation is shown in Figure 5.16. As we can see, the center of mass is within those two black lines, which means the truck is balanced at load of 2000kg.

![Figure 5.15 Forklift with 2000kg load](image_url)
Based on the results of the loading test we did above, we can say that our forklift’s maximum loading carrying capacity is 2000kg. Usually in a warehouse, we won’t put such a heavy cargo on the shelf. As to say the forklift won’t pick up such load typically. Any cargo under 2000kg could be picked up by our forklift with no problem.
Chapter 6 FEM/FEA Analysis

In previous chapters, we have already presented the design idea and dimensions (Chapter 5) and mass property of those important components (Chapter 6). These results lead us to study the design to ensure that it will meet the functional requirement including the stress analysis we are going to discuss in this chapter. We will still use the analysis tool offered by Solidworks to verify our design. The tool we are going to use here is based on finite element method and we are using it to do the stress analysis that is needed.

Finite element method is a numerical method that consists of finite element modeling (FEM) and analysis (FEA). What it does is that it divides a complex shape into lots of smaller elements when the engineering design problems are too complicated to find a closed-form solution for their governing equilibrium equation. Instead it converts the equilibrium equation of a continuum into an integral, in another word, finite element method analyzes a whole design at the element level. Those elements are adjacent to each other with no gap and connected at nodes (which are designed points of each element). Since each node has its own degrees of freedom (DOF), the selection of element type and number of nodes per element are important when we create and run an
accurate FEA for a problem. We will do the modeling (FEM) first and then analysis (FEA). We will test how safe the design and see the different results we get when using different modeling on the same design.

There are two components in the lifting fork system that need to be analyzed, one is the fork and the other one is the support frame. We will run the analysis on them separately in section 6.1 and section 6.2 to see if they are safe for use. In section 6.1, we also want to see how different element size can change the result of the meshing model and the value of stress, strain and displacement. We test the same fork under the same pressure by changing the parameters of the meshing element. Then we use the test result to get our favorite meshing element size.

In section 6.3 we will keep doing analysis on one of the most important subassembly: scissor lift. Scissor lift needs to push up not only the weight of load but also the cabin and the lifting system. We will test how it performs under the pressure and see if it is safe to use.
6.1 Fork Analysis

Forklift loading parts are responsible for picking up the load and carry it during the transportation. In this process, there are two kinds of failure: sudden fracture due to the heavy load and fatigue fracture due to the vibration caused by uneven ground during the transportation. We will do stress analysis targeting both conditions.

As Figure 6.1 shows, two components will be put under test. They are the fork and the fork support frame. As the result we get from Section 5.2.2, the maximum loading capacity of this forklift is 2000kg. So we will apply 2000kg external load to carry all analysis here.

Furthermore, as stated in finite element theory, using different meshing element would cause different analysis results. We will use the actual results to prove this conclusion.

Figure 6.1 Loading Part Analysis Demonstration
6.1.1 Forks Stress Analysis

This section covers both the static and dynamic (due to fatigue) analyses of the forks.

For the static analysis, we already got the result that the maximum loading capacity of this forklift is 2000kg. 2000kg convert to force is about 20000N. There are two forks and the structure is symmetrical, so each one of them will carry half of the force, which is 10000N. As Figure 6.2 shows, this is model we get after meshing. Then we apply a normal 10000N force on the surface of the fork. Since the top of the fork will be attached to a bar from support frame, so we will fix the top of the fork as its boundary condition, see Figure 6.3.

![Figure 6.2 Fork Meshing Model](image)

![Figure 6.3 Boundary Condition](image)
Figure 6.4 Stress Result of the Fork

Figure 6.5 Strain Result of the Fork

Figure 6.4 & Figure 6.5 is the result of the stress and strain analysis of the fork. As the figures show, the corner of the fork is red which means this part of fork is taking the biggest stress. So the corner is the place where fracture will mostly occur.
Figure 6.6 is the displacement result of the fork. As showed, the biggest displacement 11.5731mm happens at the front of the fork tip. Figure 6.7 is the FOS (Factor of Safety) analysis of the fork. The color of the fork is all blue which means the fork is safe when applied a 10000N force.
Results from Figure 6.4 – Figure 6.7 show that fork is safe under sudden loading, but we still need to check how it acts under vibration. During the transportation, the truck would vibrate due to the uneven on the ground and generates an on/off loading. Sometimes the structure will become very fragile after taking such a force for a while. To test the fork’s stability under dynamic loading, here we apply a 1000N cycle force on the fork; the result is showing in Figure 6.8. As we can see, the color of the fork is blue, which means it pass the fatigue and will be safe under periodic force.
6.1.2 Stress Analysis Using Different Mesh Element

In section 6.1.1, we already briefly introduced the meshing model of the fork. Here we will use different meshing element size in same analysis process to see how those results change (stress, strain and displacement).

Figure 6.9 Meshing Model Using Moderate Elements

Figure 6.10 Meshing Model Using Fine Elements
Figure 6.9 shows the parameter we use to create the meshing model in section 6.1.1, compare to the model in Figure 6.10, apparently since the size of the elements used in the latter one is smaller, more elements are generated in the second model.

We started with our finest element size, see Figure 6.11. The element size (L) here we use is 4mm and Figure 6.12 – Figure 6.14 is the new analysis result we get.
As we can see, the minimum and maximum stress are 0 and 253.498 MPa; the minimum and maximum strain are $2.279e^{-0.11}$ and $9.053e^{-0.04}$; the minimum and maximum displacement are $1e^{-0.3}$ and 3.891. We continue changing element parameter and the result are shown in Table 6.1.
Table 6.1 Analysis Result of Fork Model

<table>
<thead>
<tr>
<th>Element Size (L)</th>
<th>Stress (MPa)</th>
<th>Strain</th>
<th>Displacement (mm)</th>
</tr>
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<td>19</td>
<td>0</td>
<td>4.259 e-011</td>
<td>1e-030</td>
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<td>129.758</td>
<td>4.158 e-004</td>
<td>3.859</td>
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<td>20</td>
<td>0</td>
<td>4.182 e-011</td>
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<tr>
<td></td>
<td>125.433</td>
<td>4.011 e-004</td>
<td>3.859</td>
</tr>
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<td>21.36</td>
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<td>2.503 e-010</td>
<td>1e-030</td>
</tr>
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<td>4.017 e-004</td>
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<td>1e-030</td>
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<tr>
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<td>125.484</td>
<td>3.823 e-004</td>
<td>3.851</td>
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<td>3.832</td>
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</table>
Table 6.1 above shows how the results of stress, strain and displacement vary when we change the size of the element we use to run the analysis.
Figure 6.15 – Figure 6.17 are plots for all the maximum values of these three characteristics we tested. In order to make the chart according to the element number, the X-axis represents the value of “1/L”. As we can see from the table, the minimum stress is all 0, so we don’t need to include that value in the plot. The differences between the minimum strains are too small, so it can be ignored; same with the minimum displacement.
From these three plots we can see that, the change of the value is non-linearly, but with the smaller elements and increasing number of elements, the results converge to a “stable” solution in all three plots.

Figure 6.18 is the combined plot of maximum displacement, stress and strain. On the right side of the black line, all results of these three plots start to converge and become “stable”. This allows us to get the ideal finite element analysis results. The dot we are using here has the X-axis value of 0.05, which means the size of the element is 20 (L=1/0.05=20). According to Table 6.1, the maximum displacement, stress and strain of dot (L=20) is 3.859 mm, 125.433 MPa and 4.011 e-004.
Figure 6.18 Combined Plots with “Stable” Result
6.2 Fork Support Frame

Fork support frame is the part that two forks attached to. As Figure 6.19 shows, those forks were installed on the cross bar facing front with a load on top of them. After we run analysis on those forks and get the result that they won’t break after taking the load, the next thing we do here is to make sure the fork support frame is also safe to use.

![Figure 6.19 Support Frame with Load](image1)

We apply the same load as we did before: 20000N total, 10000N for each fork. The load acts on forks, and passes on to the support frame. Here we
simulate the situation by apply the force on the connecting part between forks and support frame. Figure 6.20 is the mesh model of support frame. The layer in the middle of the cross bar is defined fixed, the cross bar takes most of the stress of the load.

Figure 6.21 – Figure 6.23 are the result of stress, strain and displacement analysis. The highest stress and strain happen at the cross bar area between fork and the support frame. It is circled in Figure 6.21. This is easy to understand, since the middle layer is fixed and the forks are closer to the side frame, most pressure will concentrate on the end of the bar. The maximum stress here is 10.457 MPa and maximum strain is 5.851e^(-0.05).
Figure 6.22 Strain Analysis of Support Frame

The whole supporting frame is stable under the 20000N load. The maximum displacement happens at the front of the forks, 8.461e^(-0.01) mm.

Figure 6.23 Displacement Analysis of Support Frame
6.3 Scissor Lift

Scissor lift is the lifting device installed under the operator cabin. Its job is to push up the cabin and the whole lifting fork. So before we create the meshing model, we need to know the overall weight of the components the scissor lift is going to life. Figure 6.24 shows the mass properties is about 3230kg, which is about 31700N.

Figure 6.24 Overall Weight of the Scissor Lift Load

Figure 6.25 Scissor Lift Meshing Model
After creating the meshing model, shown in Figure 6.25, we fix the bottom of the scissor lift as the boundary condition. Considering the two hydraulic pumps is rigid here, and then we apply a 31700N force on the top of the scissor lift. Figure 6.27 – Figure 6.29 are the analysis results we get.

Figure 6.26 Boundary Condition and Applied Force

Figure 6.27 Stress Analysis of Scissor Lift
Figure 6.27 shows that the highest stress 450.771 MPa happens at the corner of the bottom case, which is the connecting point of the case and
frame, which mean when under working condition, the end of the frame (without the wheels) would take most of the pressure. Figure 6.28 the strain analysis shows that the highest strain happens at the edge of the top case where there is no support from two frames. According to the color change on the face of the top case, we know that the strain is gradually decreases when closing to the other side. The largest displacement shown Figure 6.29 happens on the face of the top case. It’s 2.222e^ (-0.01).

There is no obvious displacement in the scissor which means no break during the loading process. The whole system is overall safe for use.
Chapter 7 Design Evaluation

The technical parameters describe the structural features and performance. It includes the general parameter, dimensions, weight, performance, wheels and electronic. Those parameters will be introduced in section 7.1 with figure illustration. In section 7.2 we will discuss the advantage of our forklift design.

7.1 Parameter of the Forklift

![Figure 7.1 Top View of the Forklift](image1)

![Figure 7.2 Front View of the Forklift](image2)
Figure 7.1 and Figure 7.2 is the overall dimension of the forklift, including truck length, width, highest lifting range and highest distance from forks and ground. Table 7.1 is all the parameters that this forklift has, including dimensions, total weight, performance, tires, battery type, etc.

<table>
<thead>
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<th>Table 7.1 Lift Truck Dimensions</th>
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</tbody>
</table>

### 7.2 Advantage of the New Design

Compare to the forklift exist on the market, our design has a 180° rotate forks (connected to the cabin on both end) with a scissor lift help pushing up the operator cabin., which means it has a full loading range and the
vehicle is stable with the support of the scissor lift. In our design, these forks can be easily adapted to use other attachment, adjusted to different loading needs. With an electric battery on the back as part of the counterweight, the whole structure is stable and more economic and environmental friendly compare the ones burning gasoline.
Chapter 8 Conclusions

This project is mainly about a new design of a forklift. In Chapter 1 to Chapter 3, we did some research on the products that already exist in the market for use. Then we studied in more details about how forklifts work and the primary structure and some new design ideas were proposed. After comparing their advantage / disadvantage, we finally have our new design proposal settled and finished the 2D design schematic.

In Chapter 4 we did the next step: display our design idea in a 3D model. We used a CAD system (Solidworks) to create all individual components and assembled them to a final design. All parts are introduced in this chapter with details, including the new design scissor lift.

In chapter 5 we want to make sure our forklift design here meets the safety requirements for use. We use mass and center of gravity measurements to run our stress analysis, under both resting and loading conditions. Then we discuss the stability triangle and how our forklift design is stable under resting condition and its center of weight stays inside the safety triangle. In working conditions, we change the load to see how center of gravity of the whole truck changes and get the capacity of our forklift, which is 2000kg.

In Chapter 6 we studied the design to ensure that it will meet the
functional requirement like the stress analysis. First we ran the analysis on one of the two components in the lifting fork system, the fork. Not only we want to see if it is safe for use, we also want to see how different element type can change the result of the meshing model and the value of stress, strain and displacement. Then we ran test on the other components of the lifting system, the support frame. We also performed analysis on one of the most important subassembly, scissor lift. The result are very satisfying, they are all safe for use.

Chapter 7 gives a comprehensive technical parameter introduction. It has all the general parameters, dimensions and weight. Trucks performance and electronic system are all included here.

Future Research includes research on forklift’s weight change and stability during the turning and speeding up process, and developing a shifting counterweight automatically adjust the balance of the truck.
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