MODEL BASED OPTIMIZATION AND DEFINITION IN AN INTEGRATED
ENGINEERING DESIGN APPROACH: A CASE STUDY

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A Thesis

Presented to

the Faculty of the College of Business and Technology

Morehead State University

_____

In Partial Fulfillment

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Master of Science

_____

by

Caiwu Ding

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Accepted by the faculty of the College of Business and Technology, Morehead State University, in partial fulfillment of the requirements for the Master of Science degree.

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Dr. Hans Chapman

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Date

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Morehead State University, 2016

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Traditional engineering design process is more sequential in nature. It creates lot of design documentation. It also takes extensive amount of time to generate and operate files at different workstations. In this research, we adopt model based optimization and definition in an integrated Engineering design approach that uses advanced functionalities available in today's CAD/CAM packages, and integrates these different sequential design tasks. The application of our adopted methodology is demonstrated through a case study on engineering design of a pallet Jack.

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Chapter 1 Introduction

1.1 General Area of Concern

Traditional Engineering Design Approach

Traditional design process is more sequential in nature as shown in Figure 1.1 below. Usually there are three modules in the traditional engineering design process: CAD modeling, followed by design optimization, and then developing final working drawings. Since most of the available CAD software are focused on one or two modules, these modules get separated from each other in the industry practice, and it means the different tasks are conducted at different times and using different software packages on different workstations.
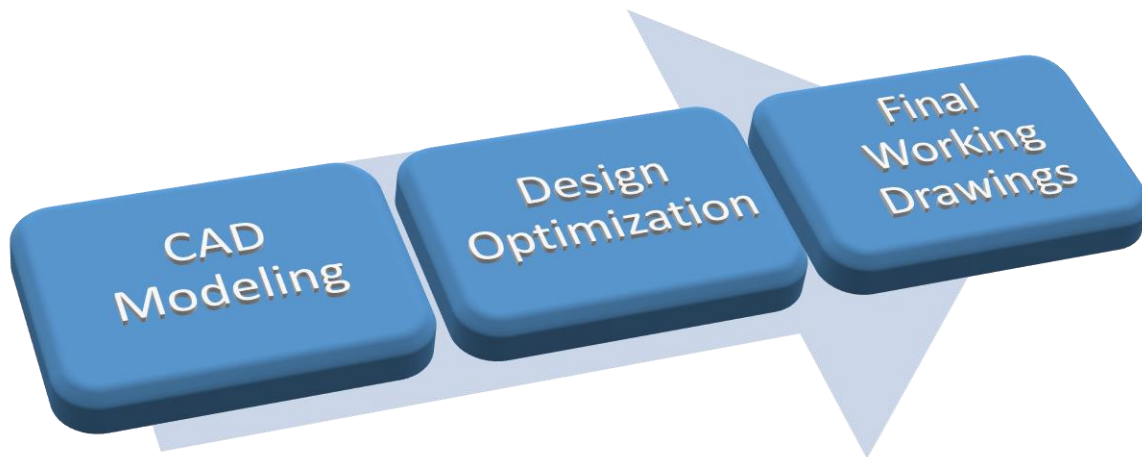

Fig.1.1: Sequential Engineering Design sub-process

The problem with this approach is it creates lot of design documentation such as separate CAD files, files with the results of design optimizations, a separate set of working drawings, etc. It also takes too much time to generate and operate files at different workstations, because transferring files between workstations is a non-value adding, and time-consuming job. Most importantly, the format inconformity of files from different workstation can be a challenge, files from one software cannot be opened in another software due to compatibility issues. Sometimes it is possible to change the file formats between programs but vast amount of time can be wasted on it; sometimes the transformation is just impossible, which means what the engineer has completed before has to be essentially redone.

In this research, we adopt a new approach that uses advanced functionalities available in today's CAD/CAM packages, and integrates these different sequential design tasks. The benefits of our adopted approach would be: less documentation, time saving, easy to operate, good format conformity, more holistic view of the product lifecycle management process. The application of our methodology is demonstrated through a case study on engineering design of a Pallet Jack.

1.2 Objective

1. Review current Engineering Design practices in industry and their limitations.

2. Research the Model-based optimization and definition advanced functionalities available in today's CAD/CAM software packages.

3. Analyze advantages and disadvantages of individual CAD/CAM packages regarding integrating difference facets of Engineering Design.

4. Adopt a new integrated design approach which will combine various phases in current Engineering Design practices into a unifying whole.

5. Demonstrate the application of our adopted approach through a case study on design of a pallet jack.

1.3 Significance and Importance of the Study

Optimization

When we are working on optimization, the object of it is to do calculation on factors such as stress, cost, deflection, natural frequency, and temperature when a part is created and set in different dimensions, loads, restraints, materials, and manufacturing requirements. Working on calculation maybe not a hard job when variables and inputs are given, however, in real engineering environment input is changing all the time or can be chosen from a big range of value. This causes huge difficulty for doing design calculation. FEA-driven optimization can solve this problem. Thanks to the progress made in computer-aided design technology and the widely usage of computer in every area of engineering, we are now able to access different kinds of software packages which promote and simplify the design process. These packages contain computer-aided engineering (CAE), computational fluid dynamics (CFD) and motion simulation.

But products that can withstand the worst case scenarios may not be the best designs in market. It is because that in order to make it meet safety and strength requirements design engineers intend to make their design too heavy or too big for their usage, or excessively expensive and difficult to manufacture. It is necessary for designers to find a way to approach to a best and most profitable product for their function, they need to turn to optimization for help. FEA-driven optimization is made to find a proper dimension for variables which can bring a best performance to the product, therefore products can gain more value and the cost of products can be reduced by reducing the amount of material used and expenses for developing the product. By employing optimization,

design engineers can save a bunch of time and increase their knowledge of their product's properties, eventually they will be able to improve upon the design based on the data obtained from previously completed analyses.

There are three main parts in optimization: objective, constrains, variables. The goal of the process is to maximize or minimize the objective by continuously modifying the variables while critical responses are within the range of defined constraints. Such as, when a company wants to be successful, minimizing weight or cost becomes the objective. (SOLIDWORKS SOFTWARE OPTIMIZATION) Constraints shape the design with really working conditions. For example, when engineers are design a gear, a constraint on the gear design can be that Contact Stress on the surfaces where two gears contact each other should be equal lower than a value. Thus the gears can stay in good working condition for a satisfied period of working life. There is no doubt that constraints are important for design consideration when products are going to work well in a real condition. Design variables are design parameters that engineers seek to change to find the best design configurations. Design variables of design optimization include material properties, dimensions, loads, size of a pattern, parameters of a spring, and so on. They can be continuous or discrete design variables. The number of variables in setting of a design optimization will has tremendous effect on the effectiveness of the analysis. In order to confirm the most reliable variables engineers in most condition would conduct an initial sensitivity studies. (SOLIDWORKS SOFTWARE OPTIMIZATION)

Trade studies, sensitivity studies, and shape optimization are the three most commonly used tools for product optimization today. For shape optimization the two most frequently used methods are gradient search and design of experiments (DoE). Trade studies method is conducted by iterating

the test of alternative design configurations. It can be highly valuable for fast evaluation of a variety of options, which can help find which changes to a part will have the most impact. SolidWorks supplies users with Configurations utility to perform the trade study iterations. After designers have determine the possible changes that are worthy of further study, a sensitivity study will be needed to search for the values of the relevant dimensions or design features.

Usually the dimension of opponents changes from one version to another for a same product. Simulation and optimization is needed when the engineers need to determine a best value for each changing design variable. Sometimes, a customized version needs to be designed based on a standard design version and according to customers' request, optimization is capable and speedy to gain an optimum design result when some variables alter as required by the customers. (SOLIDWORKS SOFTWARE OPTIMIZATION)

Model-based Definition

Because the three-dimensional design is becoming more common, traditional 2D's limitations are obvious, which is considered to be expensive and time-consuming to build and maintain; difficult to meet widely accepted industry standards and regulations. Model-based definition (MBD) is a new strategy of product lifecycle management (PLM) based on computer-aided design (CAD) models transition from simple gatherers of geometrical data to comprehensive sources of information for the overall product lifecycle. With MBD, you can communicate directly with the 3D product and manufacturing information (PMI), bypassing the time-consuming 2D process and eliminate potential problems. The adoption of MBD contributes to savings for companies in several areas, including reduced manufacturing errors, reductions in scrap and rework costs, decrease in procurement costs for purchased parts. (SOLIDWORKS MBD)

Integrated Engineering Design Approach

In this research, we adopt a new approach that uses advanced functionalities available in today's CAD/CAM packages, and integrates the three sequential design tasks in concurrent fashion. This is quite possible today with advanced standard features or add-ins available within software like SolidWorks, Pro/engineer, or Inventor. The benefits of our approach would be: less documentation, time saving, easy to operate, good format conformity, more holistic view of the product lifecycle management process. The application of our methodology is demonstrated through a case study on engineering design of a Pallet Jack. Pallet-jack is a very popular material handling equipment in the industry and a good candidate for frequent design upgrades.

1.4 Assumptions and Limitations

In this research, an incremental design optimization is performed on the existing designs of a pallet-jack instead of trying to invent a complete new design. Additionally, design for manufacturability issues are not given consideration during the design optimization phase. It is assumed that the components can be manufactured precisely within specified manufacturing tolerances. Quality related aspects of the design are also not given enough considerations. The effects of surface irregularities and surface roughness of parts in the pallet jack assembly are assumed to be zero.

1.5 Definition of Terms

1. FEA

    Finite element analysis.

2. CAE

Computer-aided engineering

3. <u>CAD</u>

Computer-Aided Design, a highly specialized form of engineering software, whose sole purpose is to create digital representations of components and systems that are to be manufactured.

4. <u>CFD</u>

CFD (Computational Fluid Dynamics) is the most popular software tool in appliance design because it characterizes fluid velocity, as well as pressure and temperature values throughout the solution domain, including complex geometries and boundary conditions.

5. <u>DOE</u>

Design of Experiments. Also known as Experimental Design, a technique for statistically testing different combinations and levels of variables on the overall outcome of an experiment.

Chapter 2: Review of Literature

2.1 Background

Typical design process is to change dimension of parts using geometry iterations, each iteration is a design calculation based on engineering analysis to find feasible value of variables. Optimization contains a large number of such design iterations to confirm the best result, it is a valuable method for engineers working on design since it simplifies and make the process faster. It can relieve the engineers by automatically performing these iterations. However, design optimization is not an alternative means and it is impossible to replace the engineer and his or her expertise with optimization in the design cycle. Because in optimization process any software cannot determine what should be optimized, and what variables can be modified to obtain a best design configuration. Thus, design optimization application will just perform as a tool of engineers. **(González)**

Most optimization problems are made up of three basic components:

1. An objective function which we want to minimize (or maximize). For instance, in designing an automobile panel, we might want to minimize the stress in a particular region.
2. A set of design variables that affect the value of the objective function. In the automobile panel design problem, the variables used to define the geometry and material of the panel.
3. A set of constraints that allow the design variables to have certain values but exclude others. In the automobile panel design problem, we would probably want to limit its weight.

2.2 Review of Literature

Optimization techniques play an important role in structural design, the very purpose of which is to find the best ways so that a designer or a decision maker can derive a maximum benefit from the available resources (Iyengar and Gupta, 1997).

In the design of structural elements, it is possible to obtain more than one feasible and safe solutions. But not all these designs may be cost-effective. But out of the possible design solutions of a structural element under a given loading conditions, only one of them will be cost effective. How to obtain this one design, called optimal design, that optimally satisfies cost effectiveness and performance is the goal of structural optimization. Structural optimization can be defined or explained in a number of ways. However, its principal objective is to find the best design out of many designs that satisfies a prescribed criterion. It can be explained as a process of maximizing or minimizing a desired objective function while satisfying the prevailing constraints. Another approach looks at it as a process of determining the optimal values of design variables that maximizes or minimizes an objective function, within the limits of imposed constraints. Structural optimization involves making decision that will result in maximum benefits from available resources (Fapohunda and Ukponu, 2014).

Structural optimization process and methodology adopted for a given problem is influenced by many factors like: (i) type of structure, (ii) model of structure, (iii), dimensionality of structure, and (iv) choice of design variables (Edgar and Lasdon, 2001).

The type of structure being optimized affects the way the process is carried out. Four types of structure are identifiable. These are: Truss, Shell, Solids, and Composite materials. (Backlund and Isby, 1988)

Engineers conceive a structure in the form in which it will be built, however, the analysis must be based on mathematical and skeletal model which approximates to the behavior of the structure in under service loads. In structural optimization process, the structural engineer will model the structure accurately in this mathematical sense. The optimization models should be such that it is close to Real-World problems. Dimensionality deals with whether it is 1-D, 2-D, 3-D structural configurations. (Allaire et al., 2004)

Modern optimization methods perform shape optimizations on components in CAD packages. Ideally, all data of components is exchanged via direct memory transfer between the CAD and FEA applications. Furthermore, any changes made in the CAD geometry are immediately reflected in the FEA model. In the approach taken by ALGOR. The engineers simply select which variables in the CAD model need to be optimized and the design constraints. The results of the analysis are compared with the design criterion. FEA model is also updated using the principle of associativity, which implies that constraints and loads are preserved from the prior analysis. The new FEA model is now analyzed, and the results are again compared with the design criterion. (González)

The design process can be described in many ways, but it must contain recognition of the need, an act of creation, and a selection of alternatives. Conventionally, the selection of the best possible alternative is the phase of design optimization. Optimization techniques play an important role in structural design, the very purpose of which is to find the best solutions from which a designer or a decision maker can derive a maximum benefit from the available resources. There can be large number of feasible designs but considering the resources the best is chosen. The best design could be in terms of minimum cost or minimum weight or maximum performance or a combination of these (Iyengar, 2004).

The existence of optimization methods can be traced to the days of Newton, Lagrange, and Cauchy. Optimization, in its broadest sense, can be applied to solve any engineering problem like design of aircraft and aerospace structures for minimum weight, optimum design of linkages, cams, gears, and other mechanical components, minimum weight design of structures for earthquake etc. (Belegundu and Chandrupatla, 1988)

While the choice of design variables plays an important role in structural optimization. In this regard, variables can be discreet (that is, material choices) or continuous (that is, physical dimensions). Variables should not be too little or too many. Using too few variables can limit the diversity of possible solutions, and thus sacrifice the optimality of the results. Also too many variables can lead to an overly complex models (Iyengar, 2004).

Structural optimization problems can be classified into three: (i) sizing optimization, (ii) shape optimization, and (iii) topology optimization. (Yamasaki et al., 2010)

Sizing optimization problems uses trusses or grillage member cross-sectional areas, plate or shell component thickness as design variables. In sizing optimization problems, the shape and topology of the analysis domain is fixed. This will help the designer to see the effect of the design variables on the member sizing. Shape optimization involves finding the right shape which will optimally perform a given function, subject to certain constraints. The very important aspect of optimization problems is that the topology of the analysis domain is fixed. Topology optimization problem is also called generalized shape or layout optimization. In this type of problems, the optimal boundary and connectivity, as well as the optimal size, shape, location, and number of other factors in an analysis domain are sought. (Allaire et al., 2004)

Chapter 3: Methodology and Case Study

3.1 Research Design

We adopt a new approach that uses advanced functionalities available in today's CAD/CAM packages, and integrates the traditional sequential design stages (CAD modeling, design optimization, final work drawings) into one single process to accelerate our design tasks. The application of our methodology is demonstrated through a case study on engineering design of a Pallet Jack. Methods in design optimization and MBD are demonstrated below in detail.

Principle in Optimization

Most of structural optimization process contains three fundamental sections: (1) design parameters, (2) constraints (equality or /and inequality), and (3) objective functions (criteria). Design parameters show the geometry and topology of the structure, also they can indicate the physical properties of the members, for example: cross-sectional variables (like areas, sectional modulus, etc), parameters that defines the structural configurations, or the material properties. Constraints are requirements that must be satisfied for the design to be acceptable and successful. They may include: stress, or deflections, or buckling, or natural frequencies, or thickness. The right choice of design parameters is termed as objective function. The choice of design parameters is either minimized or maximized or balance combination of these. Such as: (1) If this function is cost or weight of structure, it is minimized, (2) if this function is performance, or reliability, or other performance-based parameters (like energy requirement, thermal capacity, sound, insulation, etc.), it is maximized, and (3) or their combinations.

The mathematical form of an optimization problem normally looks like the following format:

Minimize or Maximize

$$F = F(x_1, x_2, x_3, \ldots\ldots\ldots x_n) \tag{1}$$

$$\left.\begin{array}{l} C_1 = C_1 (x_1, x_2, x_3, \ldots\ldots\ldots x_n) = 0 \\ C_2 = C_2 (x_1, x_2, x_3, \ldots\ldots\ldots x_n) = 0 \\ \quad \cdot\cdot \quad \cdot\cdot \quad \cdot\cdot \quad \cdot\cdot \quad \cdot\cdot \\ Cn = Cn (x_1, x_2, x_3, \ldots\ldots\ldots x_n) = 0 \end{array}\right\} \tag{2}$$

$$\left.\begin{array}{l} \alpha 1 = \alpha 1 (x_1, x_2, x_3, \ldots\ldots\ldots x_n) \geq 0 \\ \quad \cdot\cdot \quad \cdot\cdot \quad \cdot\cdot \quad \cdot\cdot \\ \alpha n = \alpha 1 (x_1, x_2, x_3, \ldots\ldots\ldots x_n) \geq 0 \end{array}\right\} \tag{3}$$

where:

F = objective function

x1, x2, x3, ... = design variables

C1, C2, ... = equality constraints

α1, α2. . . . . = inequality constraints

The nature of the mathematical programming problem depends on the functional forms of objective functions and equality constraints

Objective functions and equality constraints with different functional forms would result in different mathematical programming problems. When these are linear functions of design variables, it is a linear programming problem. Otherwise, it is nonlinear programming problem. The subject of structural optimization is to determine the manner in which the best decision on design is arrived at. It was cumbersome and tedious finding an optimal structural design until the advent of microcomputer. Numerical optimization methods have been widely applied to the optimal structural design of satellites, spacecraft's, and aircraft fuselages. It is also employed for the purpose of reducing the structural weight and satisfying the design requirements on structural properties such as improving the structural stiffness and strength, reducing the vibration levels, adjusting the natural frequencies and increasing the buckling loads. To complete all these jobs a great computation ability is needed. Nowadays engineers are supplied with variety of choices of simulation and optimization software packages, they can easily get access to the availability, simplicity of these software to optimize their design in day to day design practice. This paper demonstrates the application of design optimization in a case study.

Principle in MBD

MBD is not a tool. It is a way of managing product data that a company has to tailor within its PLM framework by using 3D models as complete sources of information for design, production, distribution, technical documentation, services, and the overall product lifecycle. In order to create a common and data management, standards and common practices should be built for all the industry. The quality function development (QFD) method has been employed to develop a sharable and reliable MBD structure. (JT Open Technology) QFD cannot support the MBD data structure and its key specifications without the involvement of stakeholders sharing CAD and PLM

knowledge in a thematic community. Thanks to a unified data structure and a comprehensive mapping of parameters (geometrical, technological, etc.), engineering information is made accessible and reusable without manual re-input of data. Moreover, data standardization allows repetitive tasks to be automated, usage methodology to be streamlined, and know-how to be translated into coded templates. Therefore, detailed simulations (logical, functional, and mechanical) can be developed from a single data source. For the manufacturing disciplines, the use of 3D models as comprehensive product/process data repository speeds up simulation tasks and makes them more controlled. (Alemanni M, Destefanis F, Vezzetti E., 2011) Computer-aided technologies (CAx) application can provide a more comprehensive set of data, allowing better integration and task automation.

3.2 Case Study

A pallet jack is a tool used to lift and move pallets. It is also known as a pallet truck, pallet pump, pump truck, dog, or jigger. Pallet Jacks are one kind of forklifts in the most basic form which are just wheels forks and the hydraulic jack itself. They are intended to be used within a warehouse to move heavy or light pallets with relative ease. They're much easier to use than using bare hands, as well as being cheaper and more efficient than a forklift for smaller loads. In most cases, you will find pallet trucks are around the same size to move standard size pallets around. Each jack's fork is around 7 inches and about a foot between them. Fork length matches up very much closely with the pallet size, usually measuring 36, 42 or 48 inches in length. Each jack can rise about 7 inches upon the ground. There are many different types of Pallet Trucks that can easily handle almost any palletized load one can imagine. The most common type of pallet jack is manual pallet jack, which is only controlled and powered by the user. Like a car jack, the operator can pump

pallet truck by hands to raise the pallets off the ground and easily wheel the load around the warehouse.

Fig. 3.1: Pallet Jack (Source: http://premierhandling.com/what-is-a-pallet-jack/)

Pallet jack is steered by a 'tiller' which also serves as a pump handle for lifting the jack. A small switch on the tiller releases the hydraulic fluid, resulting in the forks to lower. There are a pair of wheels inside the end of the forks, they are mounted on levers attached to the jack cylinder. As the hydraulic jack is raised, the links force the wheels to move down, so the forks rise vertically above the front wheels, raising the load upward until it clears the floor. The pallet is only lifted enough to clear the floor for subsequent travel. Typically, pallet jacks are used to move and organize pallets, especially in the absence of access to the forklift truck.

The first manual pallet truck was made at least before 1918. Early versions raised the forks and load only through mechanical linkages. More modern types use a hand pump hydraulic jacks to lift.

Typical dimensions:

The North American industry seems to have 'standardized' pallet jacks in several ways:

- Width of each of two Forks: 7"

- Fork Width, i.e. The dimension between the outer edges of the forks: Available as 20¼" (51.4 cm) and 27" (68.6 cm)

- Fork Length: Available as 36" (91.4 cm), 42" (106.7 cm), 48" (122 cm

- Lowered Height: 2.9" (7.5 cm)

- Raised Height: At least 7.5" (19.1), but some will raise higher

(Source: https://en.wikipedia.org/wiki/Pallet_jack)

Main components, Safety devices, Warning labels

1	Chassis	8	Parking-/ Footbrake (Option)
2	Tiller arm	9	Progressive parking and drive brake, lever with drum brake(Optional)
3	Hydraulic pump		
4	Lifting mechanism	10	Identification plate (ID-plate)
5	Steering(Front-) wheels	11	Company logo and/or capacity sticker
6	Load wheels (single/ tandem)	12	Lifting function instruction sticker
7	Lever	13	Eventually capacity sticker

Fig.3.2: Overview of a pallet jack (Source: Noblift pallet truck operating instruction document)

Main technical data

The following figure and table will show the names of technical variables and structure of a pallet

jack. In table 3.1 main technical data for standard version/other version on request is introduced in

detail.
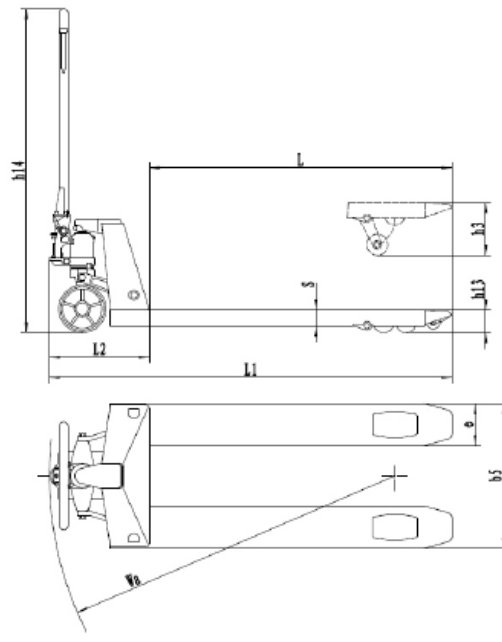
Fig. 3.3: Technical variables (Source: Noblift pallet truck operating instruction document)

Type		CBGS	CBG		CBG (Quick lift)	
					QL20H	QL20L
Load capacity	Q(t)	2.0	2.0 / 2.5		2.0	
Service weight	kg	82	66		83	82
Tyre size, front	mm	⌀200x50	⌀200x50	⌀180x50	⌀200x50/ ⌀180x50	⌀180x50
Tyre size, rear (single/ tandem)	mm	-- / ⌀82x70	⌀80x93/ ⌀80x70	⌀74x93/ ⌀74x70	⌀80x93/ ⌀80x70	⌀74x93/ ⌀74x70
Wheels nr. front, rear		Xx, 2/4	2/2, 2/4		2/2, 2/4	2/2, 2/4
Height of tiller	h14 (mm)	1230	1230		1230	1230
Height, lowered	h13(mm)	85	85	75	85	75
Lift	h3(mm)	115	115		115	115
Overall length	L1(mm)	1555	1555		1555	1555
Fork dimensions	s/e/L (mm)	160/60/1150$^{1)}$	160/60/1150$^{2)}$, 150/50/1150$^{2)}$		160/60/1150$^{2)}$, 150/50/1150$^{2)}$	
Distance betw. forks	b5(mm)	540/ 685	520/550/685		520/550/685	

Type		DF						DF168
		DF 20		DF 25		DF 30		
Load capacity	Q(t)	2.0		2.5		3.0		1.68
Service weight	kg	62		64		80		50/ 56
Tyre size, front	mm	⌀200x50	⌀180x50	⌀200x50	⌀180x50	⌀200x50	⌀180x50	⌀180x50
Tyre size, rear (single/ tandem)	mm	⌀80x93/ ⌀80x70	⌀74x93/ ⌀74x70	⌀80x93/ ⌀80x70	⌀74x93/ ⌀74x70	⌀80x93/ ⌀80x70	⌀74x93/ ⌀74x70	⌀83x70/ ⌀73x55
Wheels nr. front, rear		2/2, 2/4		2/2, 2/4		2/2, 2/4		2/2, 2/4
Height of tiller	h14 (mm)	1230		1230		1230		1230
Height, lowered	h13(mm)	85	75	85	75	85	75	75
Lift	h3(mm)	115		115		115		115
Overall length	L1(mm)	1530		1530		1530		1530
Fork dimensions	s/e/L (mm)	160/60/1150$^{2)}$		160/60/1150$^{2)}$		160/60/1150$^{2)}$		150/50/1150
Distance betw. forks	b5(mm)	450/ 520/ 550/ 685		450/ 520/ 550/ 685		450/ 520/ 550/ 685		520/ 550

Type		DFE20	L series			L60/SL (Low Profile)
Load capacity	Q(t)	2.0	2.0	2.5	3.0	1.5
Service weight	kg	50/60	77	78	83	107
Tyre size, front	mm	φ180×50	φ200×50/φ180×50			φ180×50
Tyre size, rear	mm	φ73×80/φ73×55	φ74×93/φ74×70			φ44×70
Wheels nr. Front, rear		2/2, 2/4	2/2, 2/4			2/4 ,
Height of tiller	h14(mm)	1230	1180			1180
Height, lowered	h13(mm)	75	75			47
Lift	h3(mm)	115	110			108
Overall length	L1(mm)	1530	1525			1525
Fork dimensions	s/e/L(mm)	150/50/1150	177/45/1150			177/35/1150
Distance betw. Forks	b5(mm)	520/550/685	520/550/685			520/685/838

he noise level is less than 70dB.
1) L=1220 mm optional
2) L= 800/ 900/ 1000/ 1100/ 1220 mm optional

Table 3.1: Main Technical data for standard version/other version on request (Source:

Noblift pallet truck operating instruction)

3.2.1 CAD Modeling
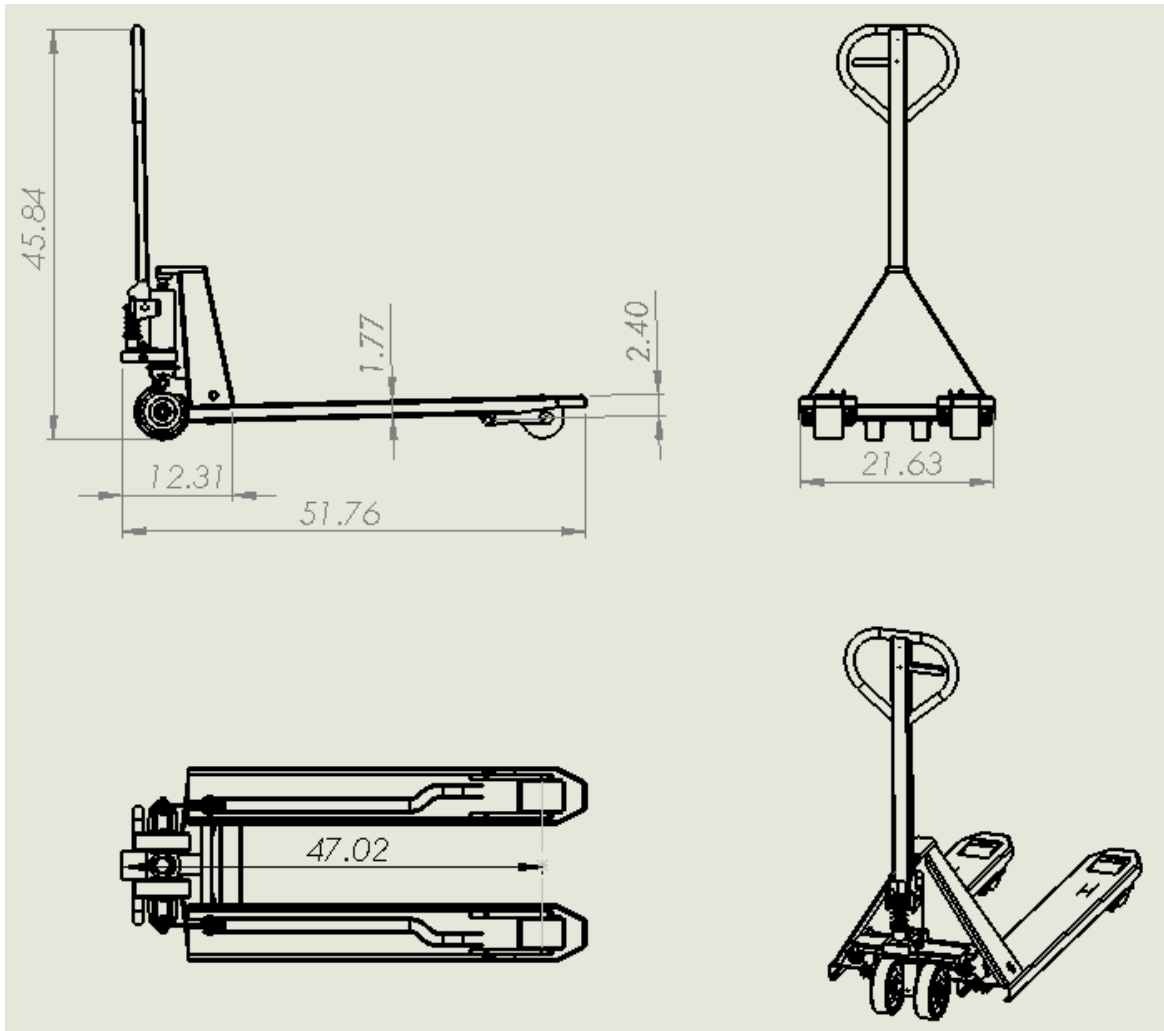
Fig. 3.4: Important variables in the developed CAD model of the pallet jack for the case study
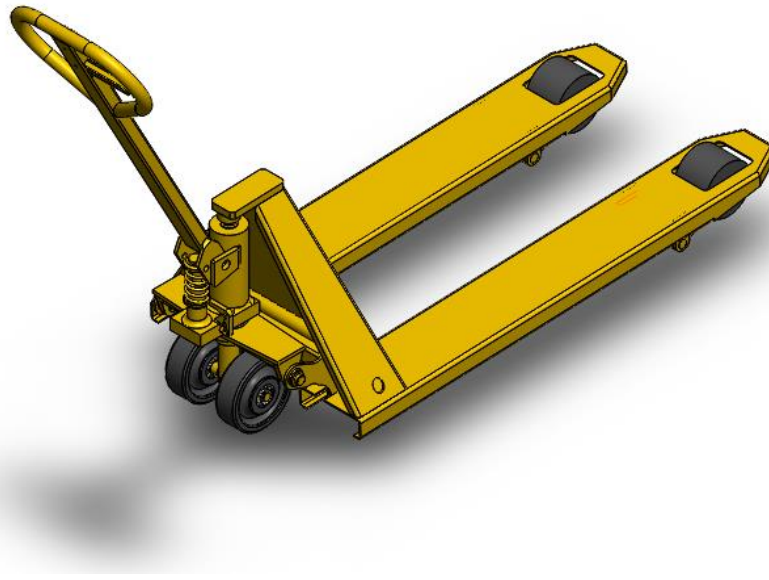
Fig. 3.5: Developed CAD model of the pallet jack

3.2.2 Simulation & optimization Methodology
The main steps for simulation & optimization are outlined below:

1. Create a study case;
2. Design study case (variables, range, constraints);
3. Design study option;
4. Result view.

We used Solidworks 2015 software to perform simulation and optimization on the case study of the pallet jack. Several screenshots shown below explains how the four steps outline above were performed within Solidworks CAD modeling environment.

Step 1. Create a study case

1. Open a new study
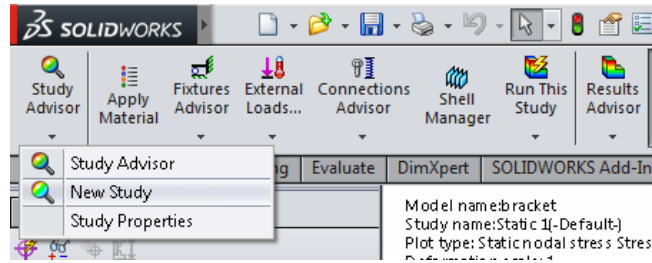
Fig.3.6: new study

2. Select "Static" from Type of Study for the static study.
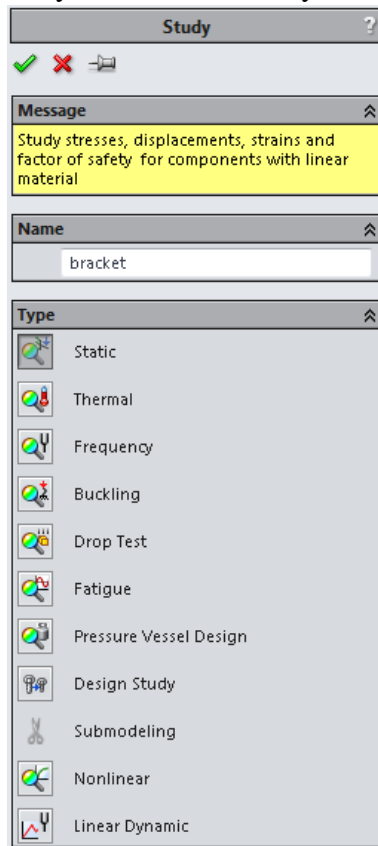
Fig.3.7: Type of study

3. In Simulation Management Tree, right click on "Fixtures" and select "Fixed Hinge"
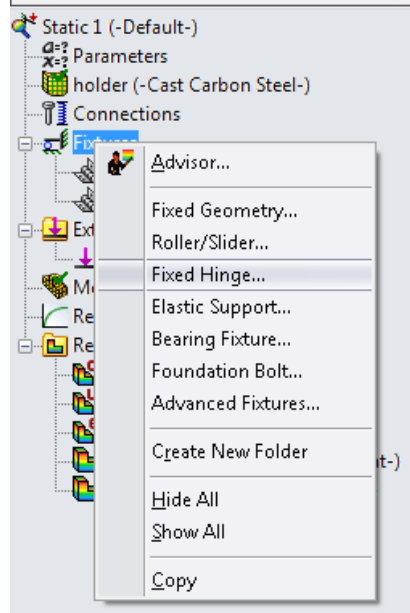
Fig.3.8: Fixture

4. Define the hinges by choosing faces for fixture, two faces are selected. And then set the two cylindrical faces on right upper corner as fixed hinges
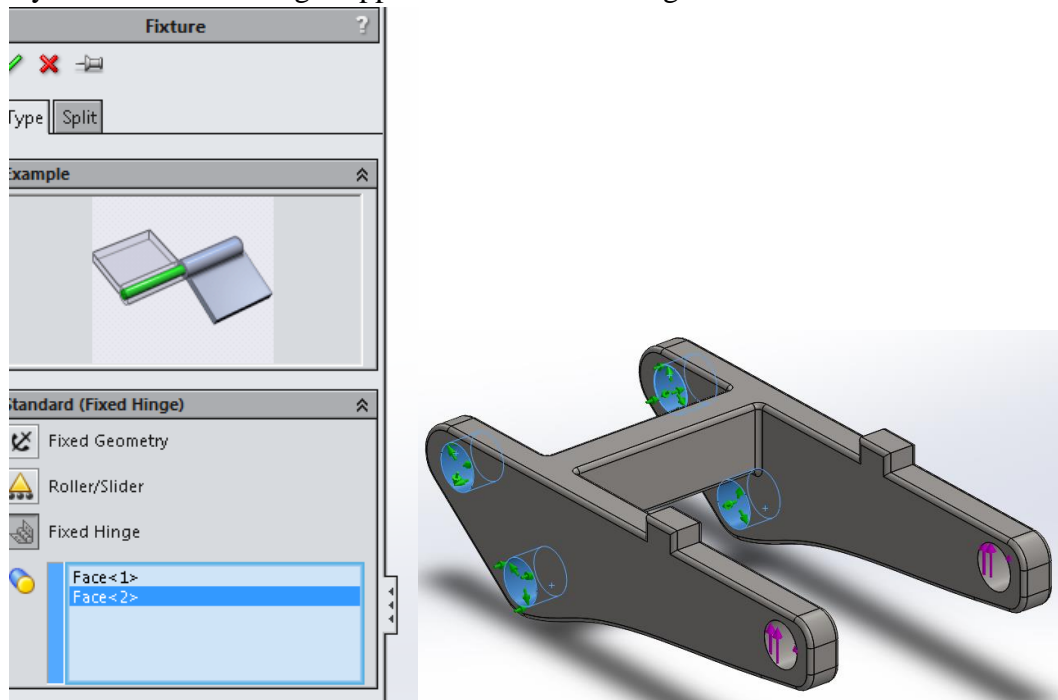
Fig.3.9: Setting of Fixture

5. Define external force for the static study as shown in Figure 3.10.
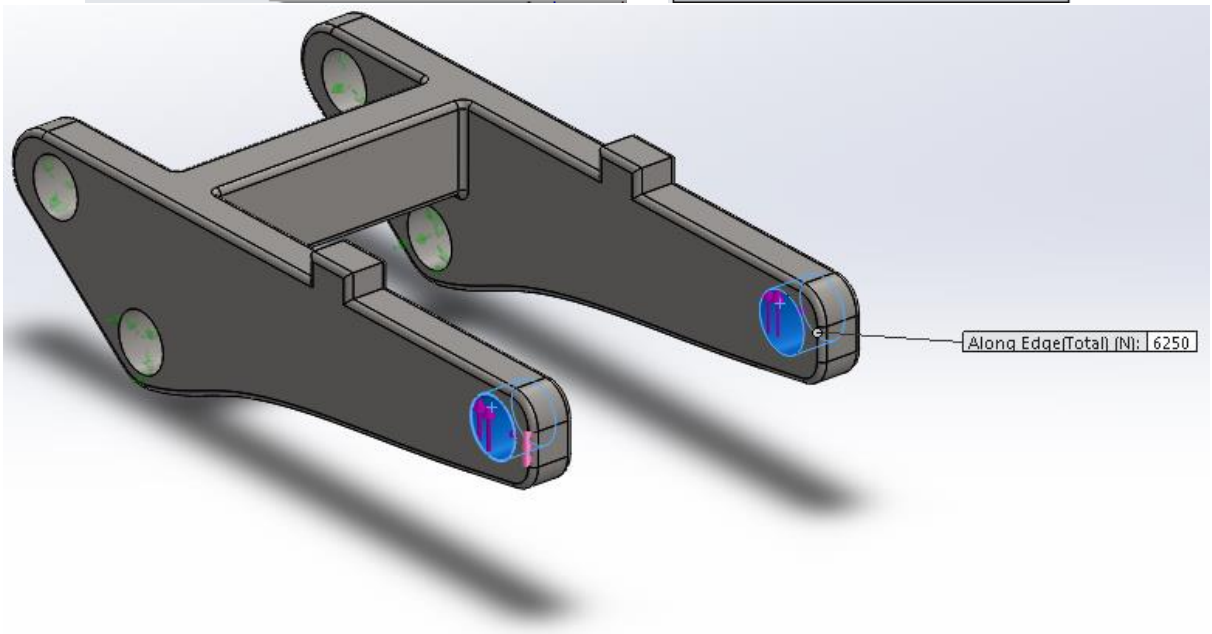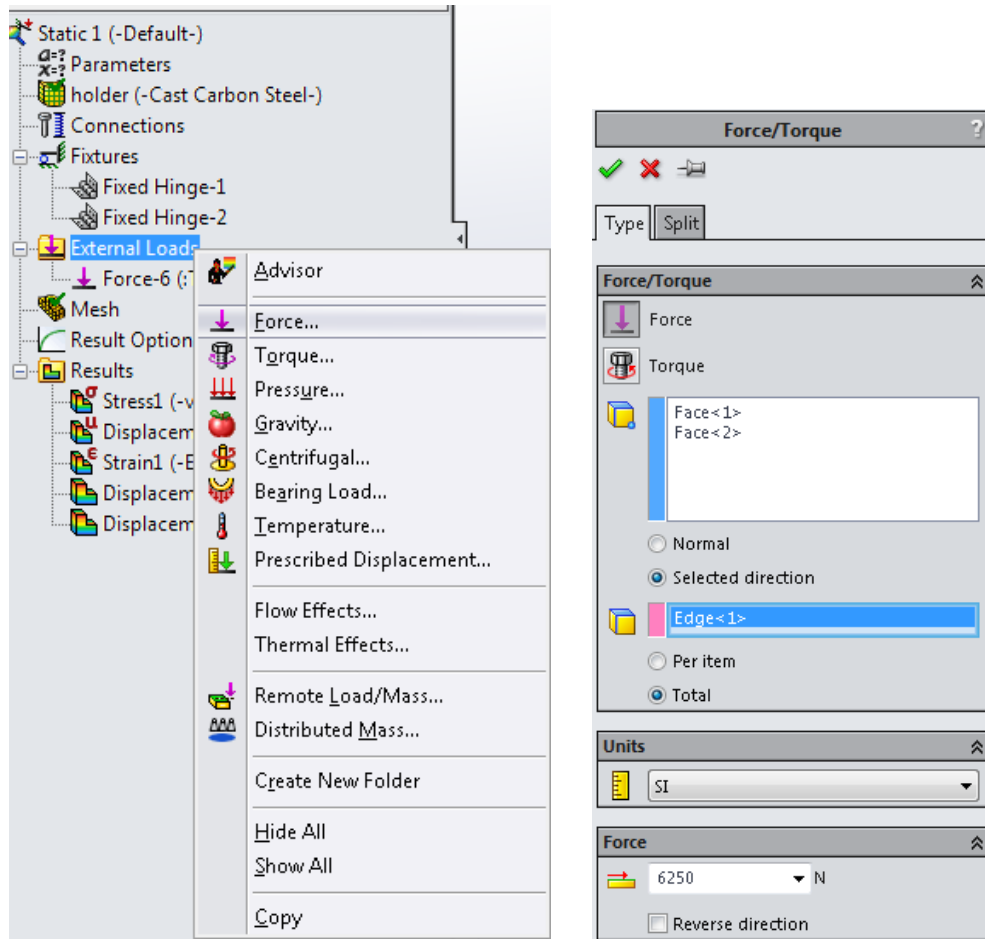
Fig.3.10: Define External Force

6. Right click on "Mesh" and choose "Create Mesh"
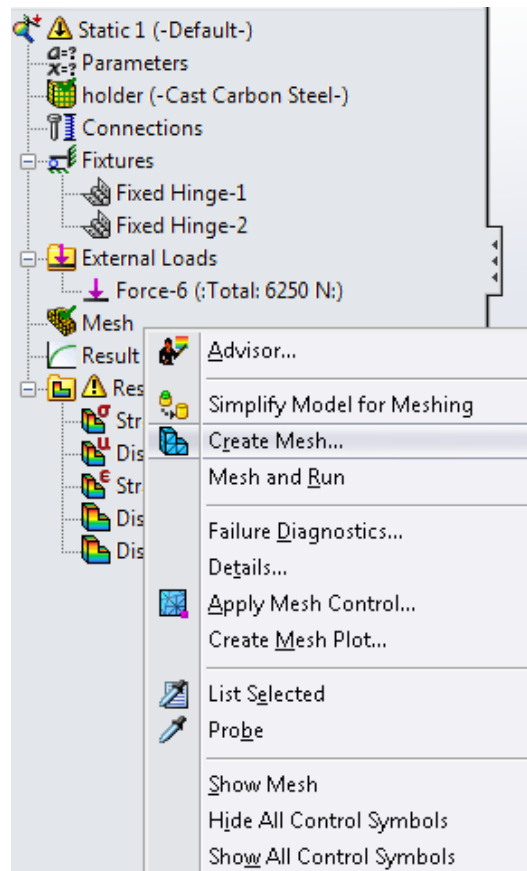
Fig.3.11: Mesh

7. Press "Run This Study" to generate results
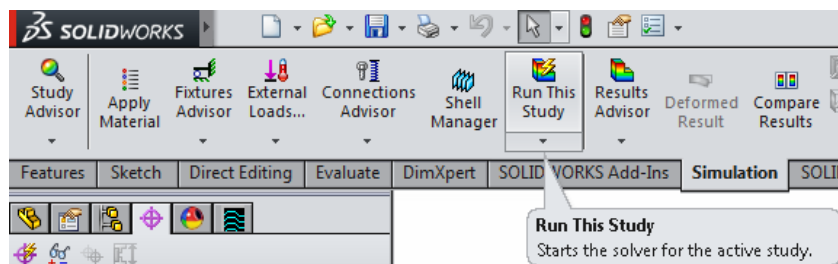
Fig.3.12: Run Study

Step 2. Design study case (variables, range, constraints)

Design optimization is to find the best design by changing geometry. In the design study case, some questions that need to be addressed first are:

Objectives of the design optimization process:

Select the objectives to optimize that defines the best design. Some examples are:

- Minimize volume or mass

- Maximize or minimize resonance frequency

Design Optimization variables

Design variables are the changeable in the model. Any dimension can be set as a design variable. For each design variable, you need to specify the lower and upper limitation of value as well as the tolerance.

Design Optimization Constraints

Set the conditions that the optimum parameters of our design must satisfy. For example, stresses should not exceed the yield strength of material we use to make the part and the natural frequency should be in a specified range to avoid serious resonance, etc.

According to the process, before creating an optimization study, we have to create one or more simulation study (Static or Frequency or Buckling or Thermal) that we can use in design optimization to define the objective function and constraints.

Operations for Design Study:

1. Click on "Evaluate" tab and choose "Design Study" to create a new design study
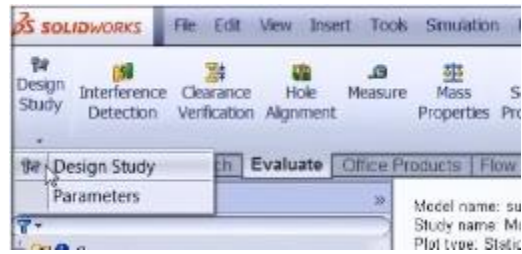
Fig.3.13: new design study

2. Define design variables by adding new parameters

Go to the "View" menu and on the drag-down list select "All Annotation"; then right click on "Annotation" in design tree and ensure "Show Feature Dimensions" are selected.
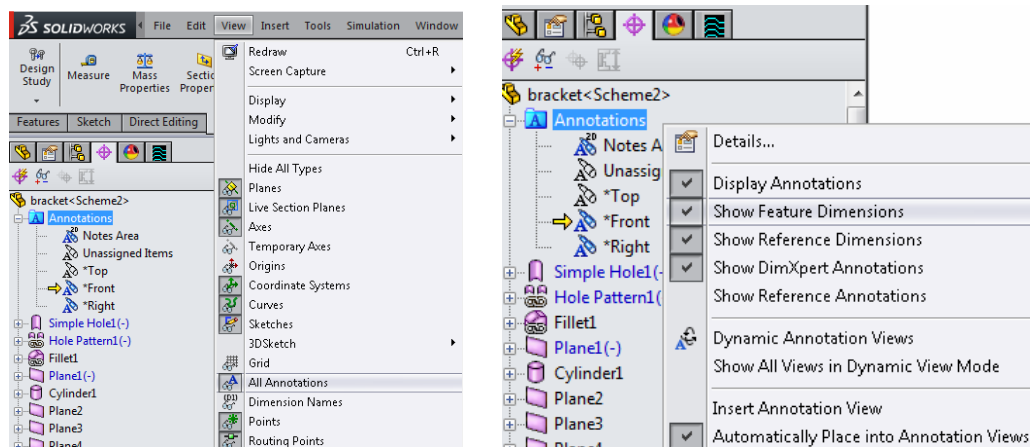
Fig.3.14: setting of view

Click on "Add Parameter" and create a new parameter by choosing a feature Dimension from the 3D model, set the category as "Model Dimension"
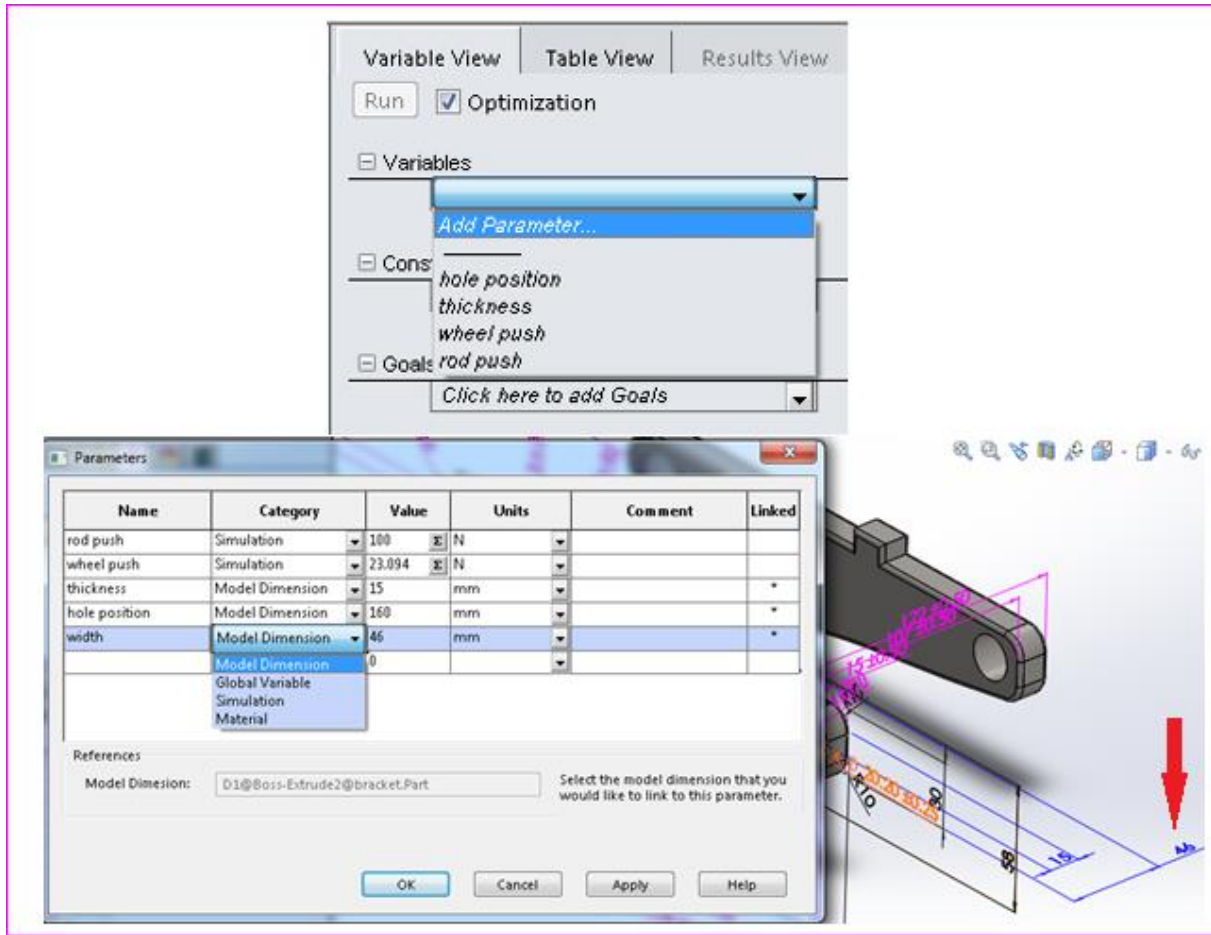
Fig.3.15: Add Parameter

3. Set "Constraints" and "Goals" as shown in Figure 3.16.
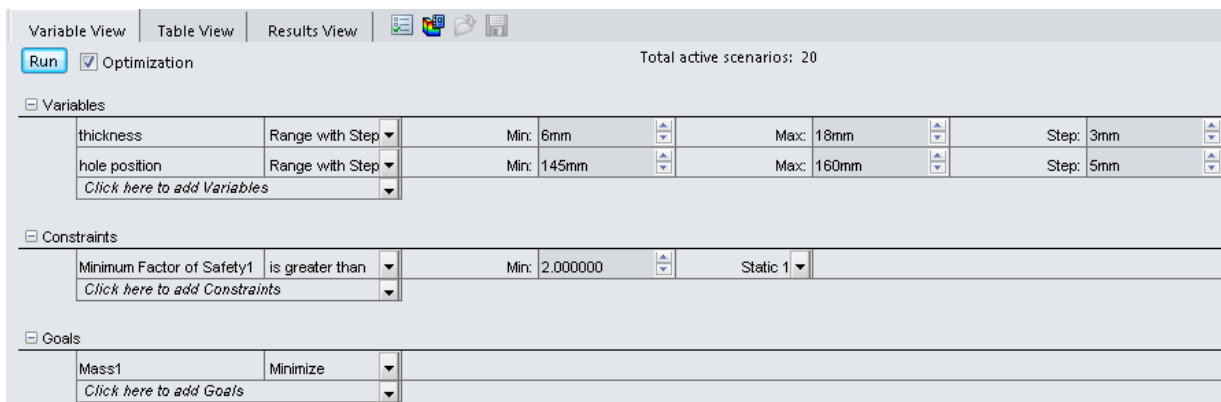
Fig.3.16: Variable View

Step 3. Design study option

Go to "Design Study Option" and choose "High quality (slower)"
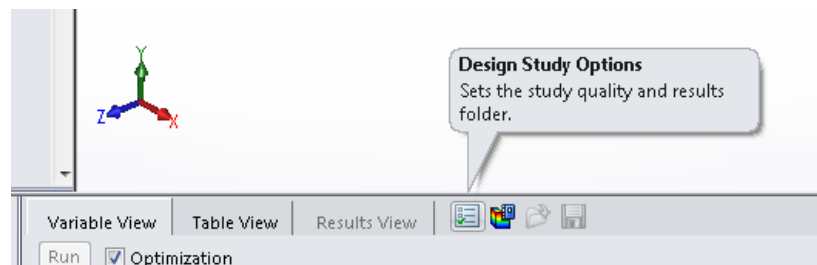
Fig.3.17: Design study option

Step 4. Result view

Click "run" with Optimization selected and wait for optimization result
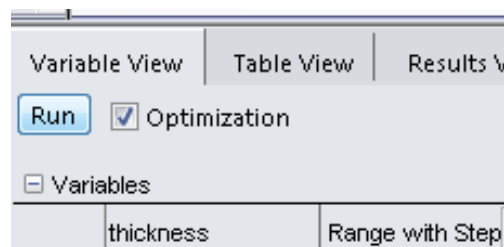
Fig.3.18: Run Optimization

3.2.3 Model Based Definition:
Model Based Definition procedure is explained in detail below:

1. Select "SolidWorks MBD" and click on "Auto Dimension Scheme", then choose

    "Primary Datum" and "Secondary Datum" from the model and click "OK".
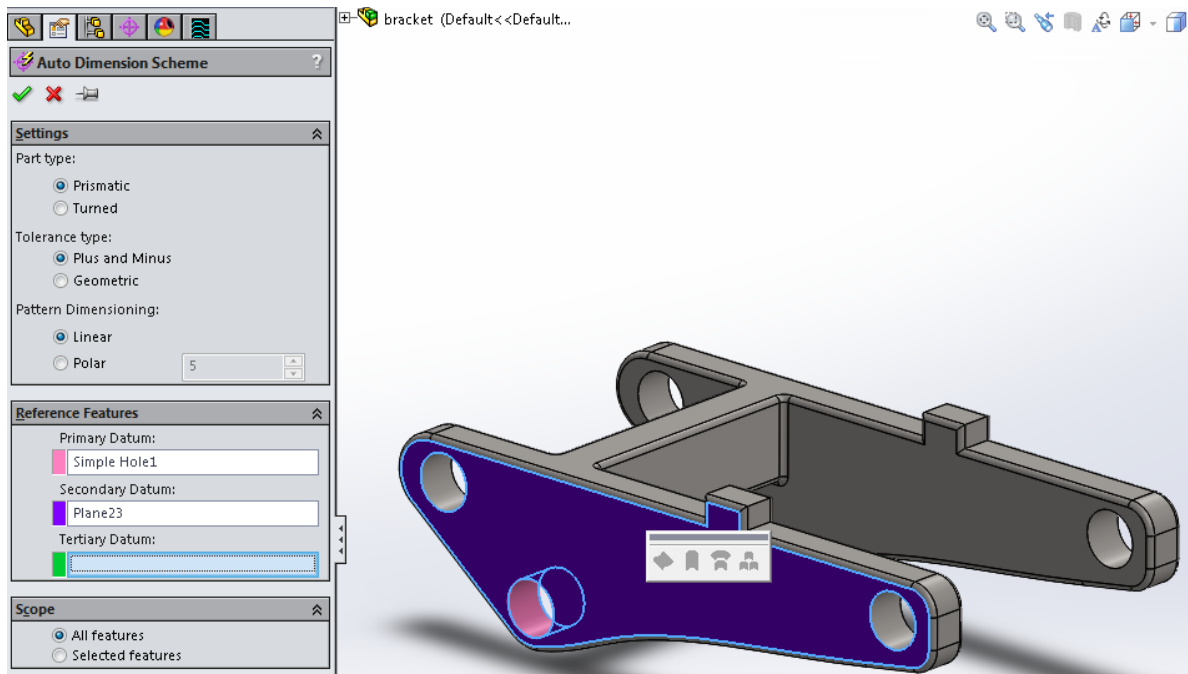
Fig.3.19: auto dimension scheme

2. Click on "3D Views" tab at the bottom, modify and adjust the view of model dimensions

   and click "Capture 3D View" to generate a 3D view
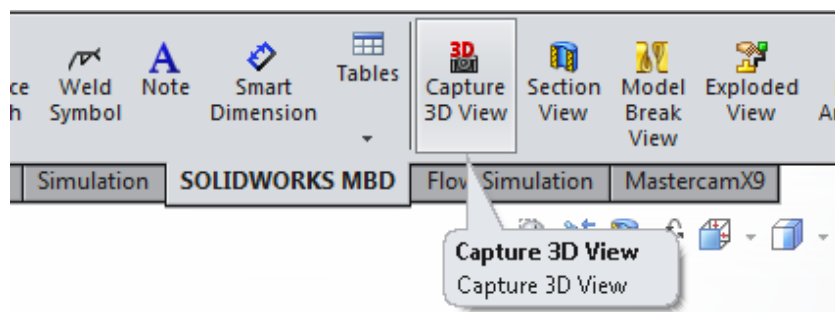
Fig.3.20: Capture 3D views

3. Make 3D views as needed depending on the configuration of model

   What MBD exactly does: Engineers can communicate and transfer product and

   manufacturing information (PMI) directly in 3D.This 3D MBD contains data including

   dimensions product models, surface finishes, bill of materials (BOM), notes, geometric

   tolerances, welding symbols, callouts, tables, Meta properties, and other annotations.
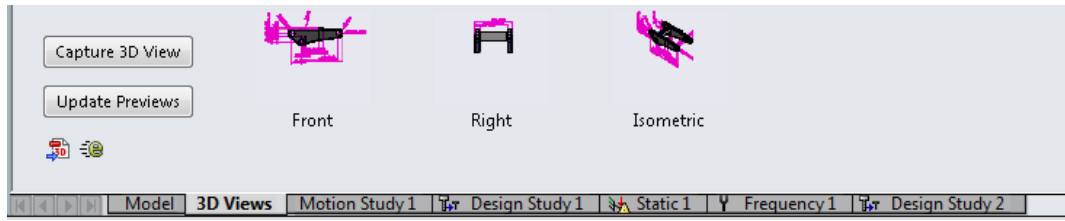
Fig.3.21: 3D views

Chapter 4: Results and Conclusions

Simulation and optimization procedures are performed on the two critical parts of the developed CAD model of the pallet jack, the bracket and the basis for the demonstration purpose and the results are documented below.

4.1 Results and conclusions of Part 1: the bracket (simulation, optimization, and MBD results)

Simulation and Optimization Results:

The general mathematical form of the design optimization is:

Minimize or Maximize

$$F = F\ (x_1, x_2, x_3, \ldots\ldots\ldots\ldots x_n) \tag{1}$$

$$\left.\begin{aligned}
C_1 &= C_1\ (x_1, x_2, x_3, \ldots\ldots\ldots\ldots x_n) = 0 \\
C_2 &= C_2\ (x_1, x_2, x_3, \ldots\ldots\ldots\ldots x_n) = 0 \\
&\ \cdots \quad \cdots \quad \cdots \quad \cdots \quad \cdots \\
Cn &= Cn\ (x_1, x_2, x_3, \ldots\ldots\ldots\ldots x_n) = 0
\end{aligned}\right\} \tag{2}$$

$$\left.\begin{aligned}
\alpha 1 &= \alpha 1\ (x_1, x_2, x_3, \ldots\ldots\ldots\ldots x_n) \geq 0 \\
&\ \cdots \quad \cdots \quad \cdots \quad \cdots \\
\alpha n &= \alpha 1\ (x_1, x_2, x_3, \ldots\ldots\ldots\ldots x_n) \geq 0
\end{aligned}\right\} \tag{3}$$

Where F is the objective function to optimize, x_n's indicate the design variables, C_n's indicate the equality constraints, and α_n's indicate the non-equality constraints.

In case of the bracket optimization problem,

F = Minimize Mass (objective function)

x_1, and x_2 are the thickness, and the hole position respectively (design variables)

α_1 is the Factor of Safety (inequality constraints) ≥ 2

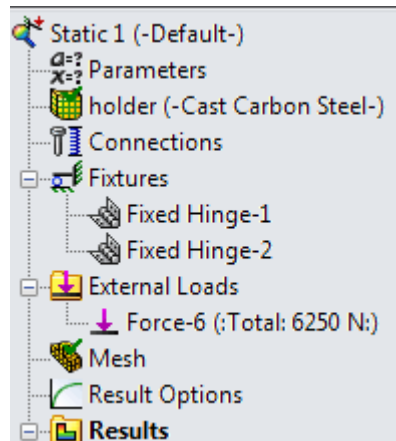Setting of the static study for the Bracket:

Fig.4.1: Setting of the Static Study

6250 N external force in total is applied to the right-side holes on Bracket as indicated by the

pink arrows in Fig 4.2. The direction of external force is same as the direction of the pink arrows.

Two groups of Fixed Hinge are put on the part on the left side shown by green arrows in Fig 4.2.

Fig 4.2 shows Von-mises stress analysis for the bracket. It tells engineers the stress value on

different area of the part by creating a spectrum marked with corresponding stress value for

different color. Yield strength for it is 2.482e+008 N/m^2. It means the part is not going to be

broken when external force is applied.
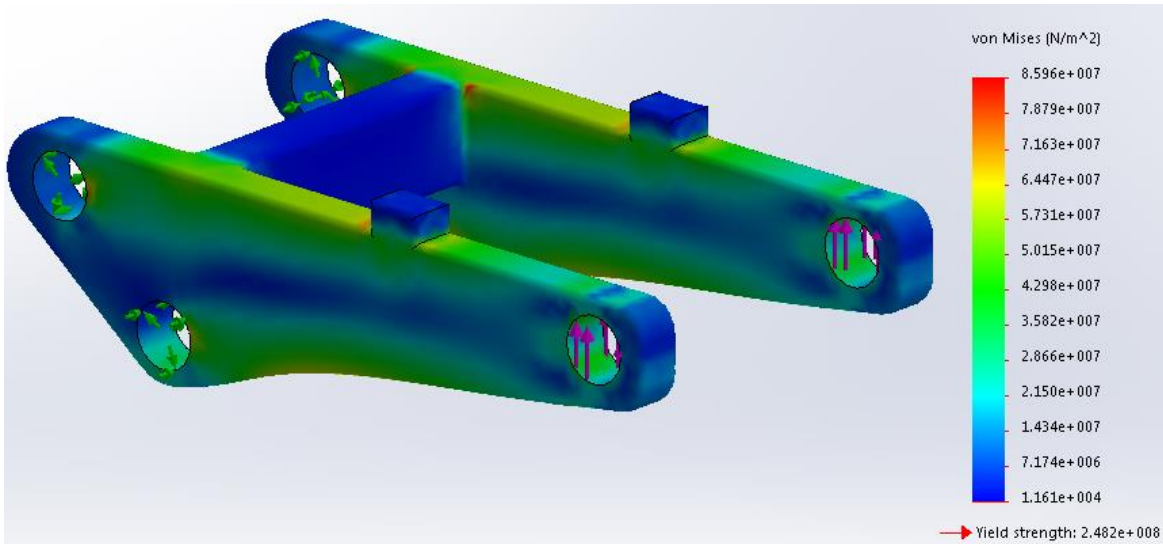
Fig.4.2: Von-mises Stress developed in the bracket

Fig 4.3 shows Displacement analysis for the bracket. It displays displacement of different place on the part. Section in red has the highest level of displacement, blue section has smallest displacement. Values corresponding to colors are indicated.
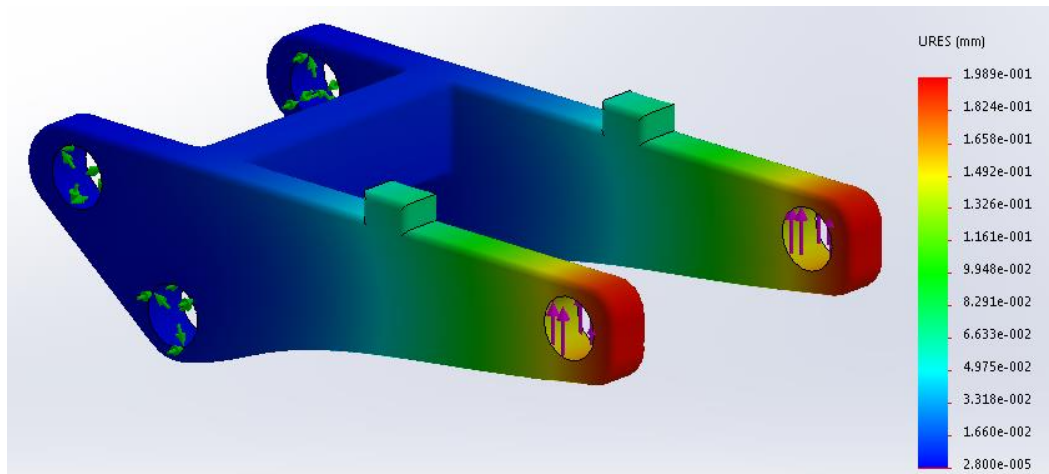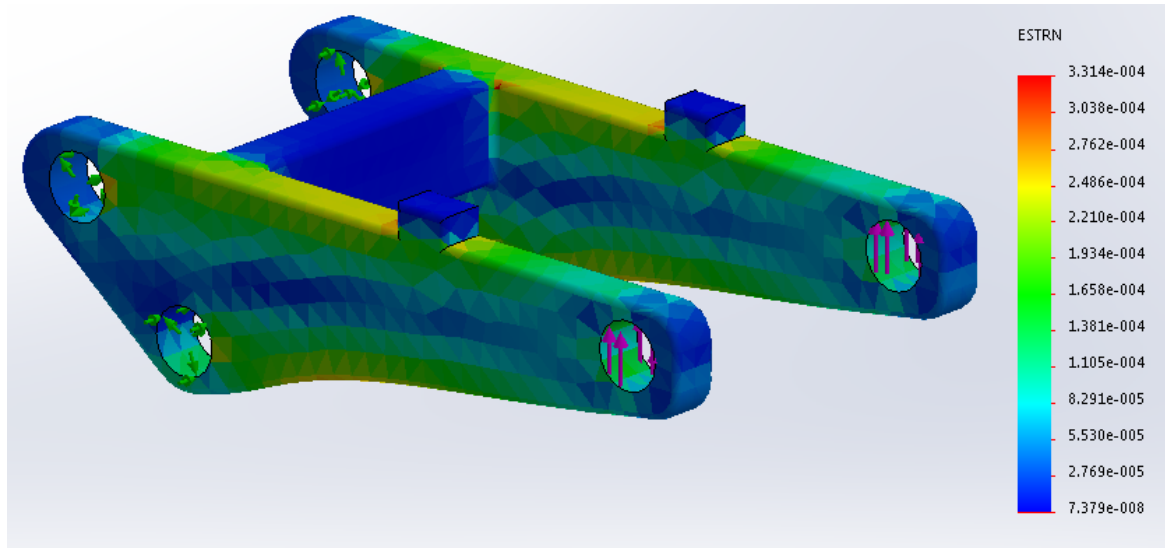

Fig.4.3: Displacement graph for the bracket

Fig 4.4 shows Strain analysis for the bracket. It displays strain of different place on the part. Section in red has the highest level of strain, blue section has lowest strain. Values corresponding to colors are indicated.

Fig.4.4: Strain graph for the bracket

Fig 4.5 shows result of optimization for the bracket. "Thickness" and "Hole position" are names of the two variables. Constraint for this optimization is Minimum Factor of Safety should be over 2. Object is set to minimize mass of the part. There are 20 scenarios for this analysis, and groups in red are not feasible design, the green one is our optimal result.

		Current	Initial	Optimal (2)	Scenario 1	Scenario 2	Scenario 3	Scenario 4
thickness		15mm	15mm	9mm	6mm	9mm	12mm	15mm
hole position		160mm	160mm	145mm	145mm	145mm	145mm	145mm
Minimum Factor of Safety1	> 2.000000	2.760863	2.760863	2.005560	1.267586	2.005560	2.604139	3.046640
Mass1	Minimize	2484.41 g	2484.41 g	1689.17 g	1291.55 g	1689.17 g	2086.79 g	2484.41 g

Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11	Scenario 12	Scenario 13
18mm	6mm	9mm	12mm	15mm	18mm	6mm	9mm	12mm
145mm	150mm	150mm	150mm	150mm	150mm	155mm	155mm	155mm
3.750712	1.163786	1.964543	2.536217	3.088025	3.324582	1.103363	1.904460	2.394242
2882.03 g	1291.55 g	1689.17 g	2086.79 g	2484.41 g	2882.03 g	1291.55 g	1689.17 g	2086.79 g

Scenario 14	Scenario 15	Scenario 16	Scenario 17	Scenario 18	Scenario 19	Scenario 20
15mm	18mm	6mm	9mm	12mm	15mm	18mm
155mm	155mm	160mm	160mm	160mm	160mm	160mm
2.879193	3.472961	1.029982	1.855568	2.303242	2.815228	3.263179
2484.41 g	2882.03 g	1291.55 g	1689.17 g	2086.79 g	2484.41 g	2882.03 g

Fig.4.5: result of optimization for the bracket

Model Based Definition (MBD) Results for the Bracket:

Figures 4.6, 4.7, and 4.8 show different views of the Bracket developed as part of the Model-based definition of the part. Figure 4.9 show the 3D pdf document generated by the SolidWorks MBD module.
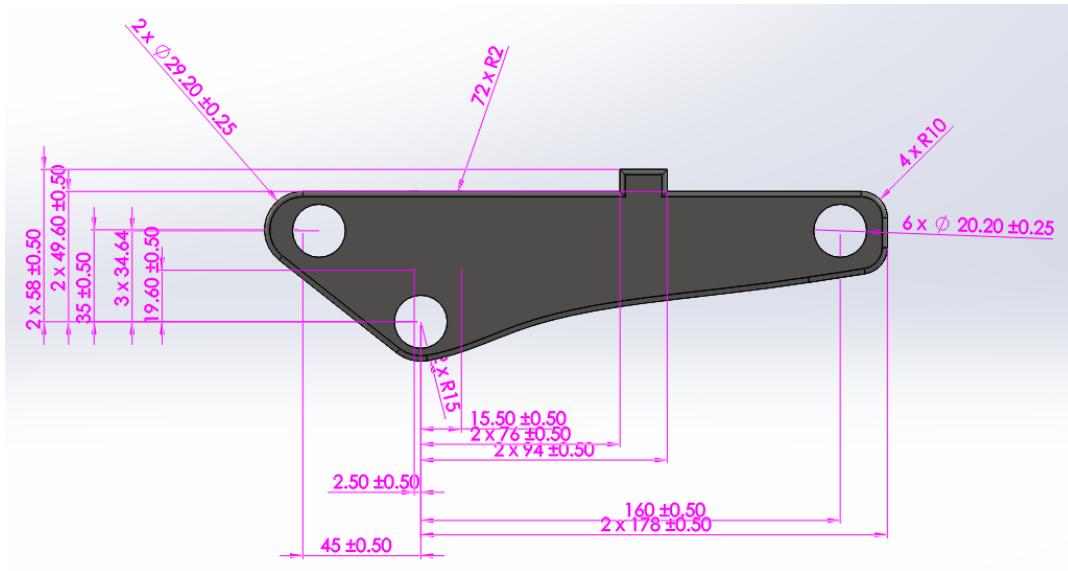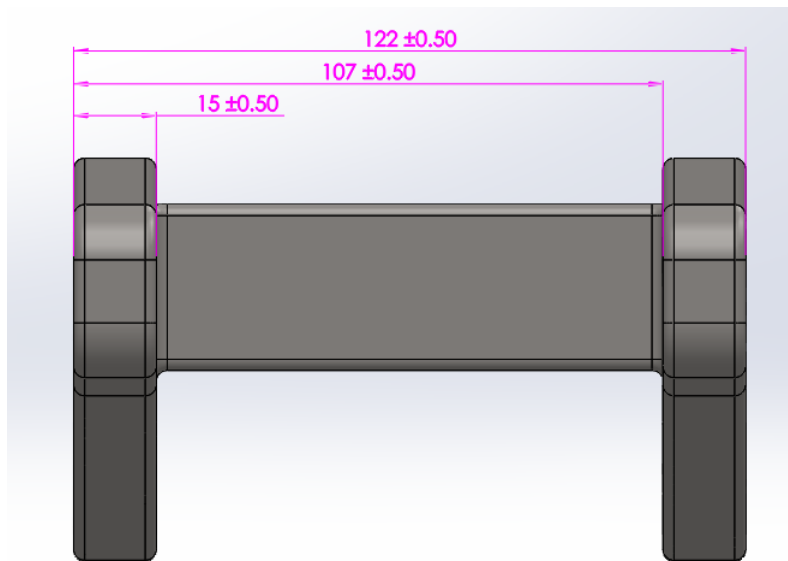
Fig.4.6: Frnt view of the Bracket
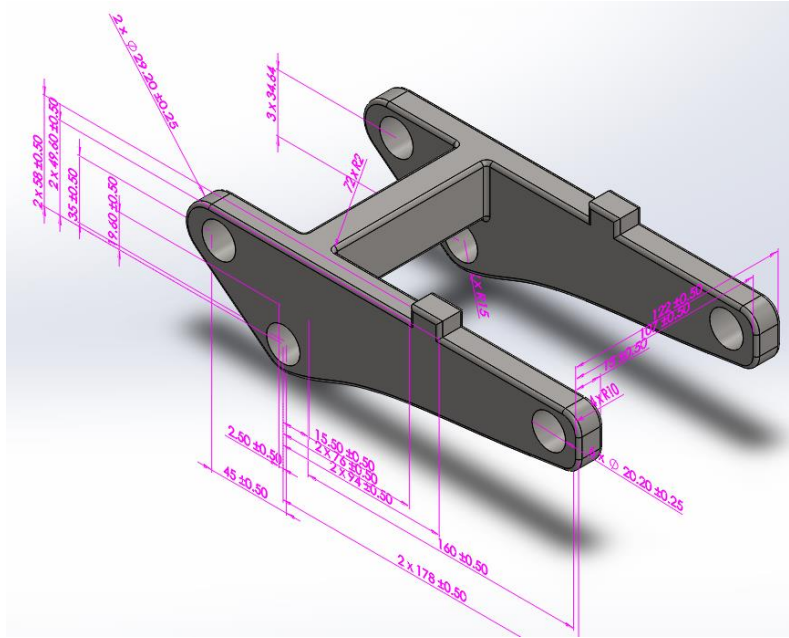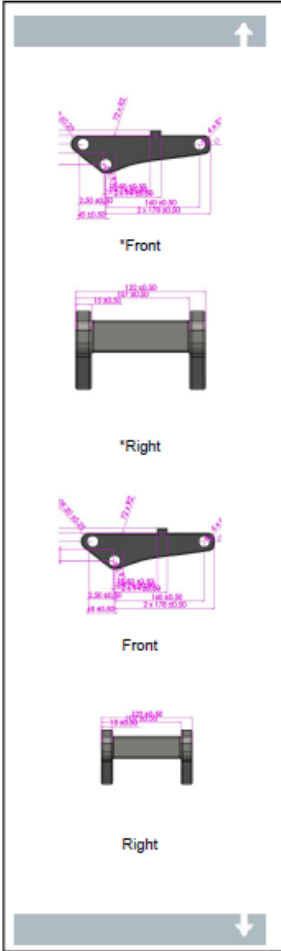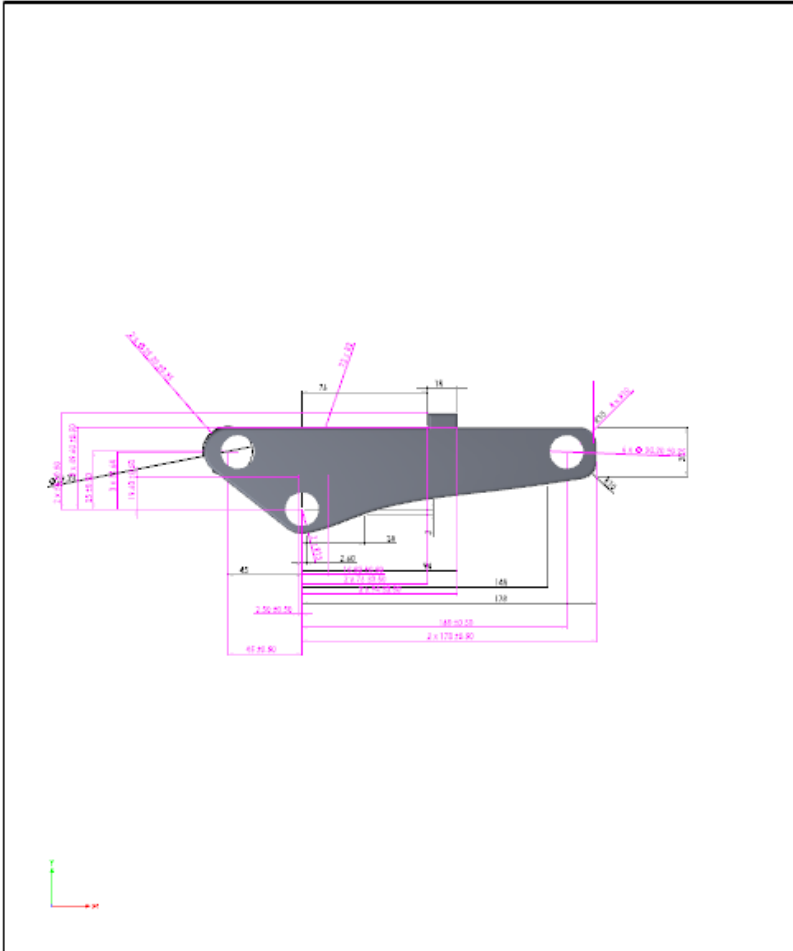

Fig.4.7: Right View of the Bracket

Fig.4.8: Isometric view of the Bracket

Part Number:		Date:	4/6/2016
Comments:	IT IS DESIGNED FOR JACK PELLET FOR CAIWU'S THESIS	Revision: Material:	
		Designed by:	CAIWU

*Front

*Right

Front

Right

Notes:

NOTES: UNLESS OTHERWISE SPECIFIED:
1. INTERPRET THIS DRAWING PER ASME Y14.5M-1994
2. BREAK ALL SHARP CORNERS.
3. ALL DIMENSIONS IN INCHES. DO NOT SCALE PRINT.
4. ALL RUST, SCALE AND DEBRIS MUST BE REMOVED.
   SURFACE RUST, ONLY, ALLOWED ON CAST SURFACES.

5. TOLERANCES: MACHINED   FORMED

Fig.4.9: 3D MBD PDF of the Bracket

4.2 Part 2: Basis

Simulation and Optimization Results:

In case of the optimization problem for the basis,

F = Minimize Mass (objective function)

x_1, and x_2 are the thickness 1, and thickness 2 respectively as shown in Fig 4.9(design variables)

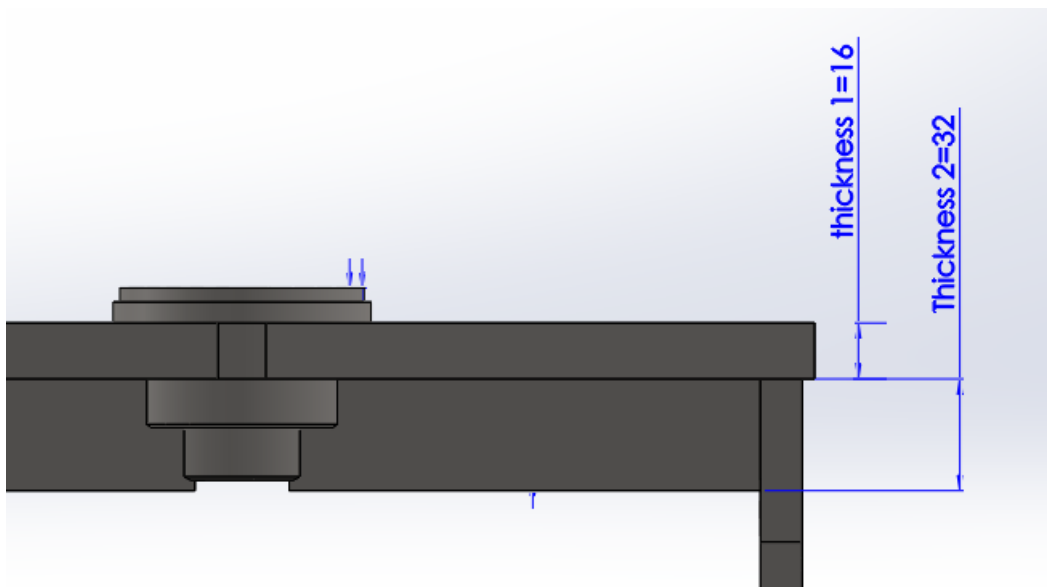α_1 is the Factor of Safety (inequality constraints) $\geq$ 2

Fig 4.10: Design Variables

Fig 4.11 shows Von-mises stress analysis for the Basis. It tells engineers the stress value on different area of the part by creating a spectrum marked with corresponding stress value for different color. Yield strength for it is 2.482e+008 N/m^2. It means the part is strong enough.

von Mises (N/m^2)

1.097e+008
1.006e+008
9.145e+007
8.231e+007
7.317e+007
6.403e+007
5.489e+007
4.575e+007
3.661e+007
2.747e+007
1.833e+007
9.185e+006
4.507e+004

➡ Yield strength: 2.482e+008
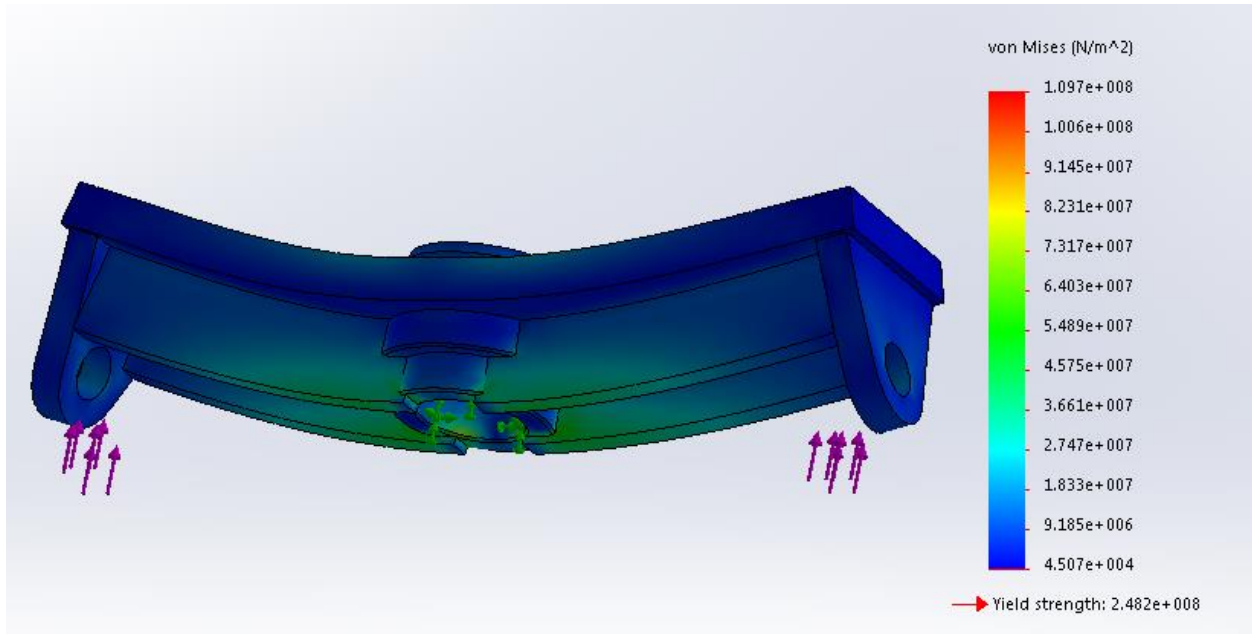
Fig.4.11: Von-mises Stress Diagram for Basis

Fig. 4.12 shows Displacement analysis for the Basis. It displays displacement of different place on the part. The section in red has the highest level of displacement, the blue section has smallest displacement. Values corresponding to colors are indicated.
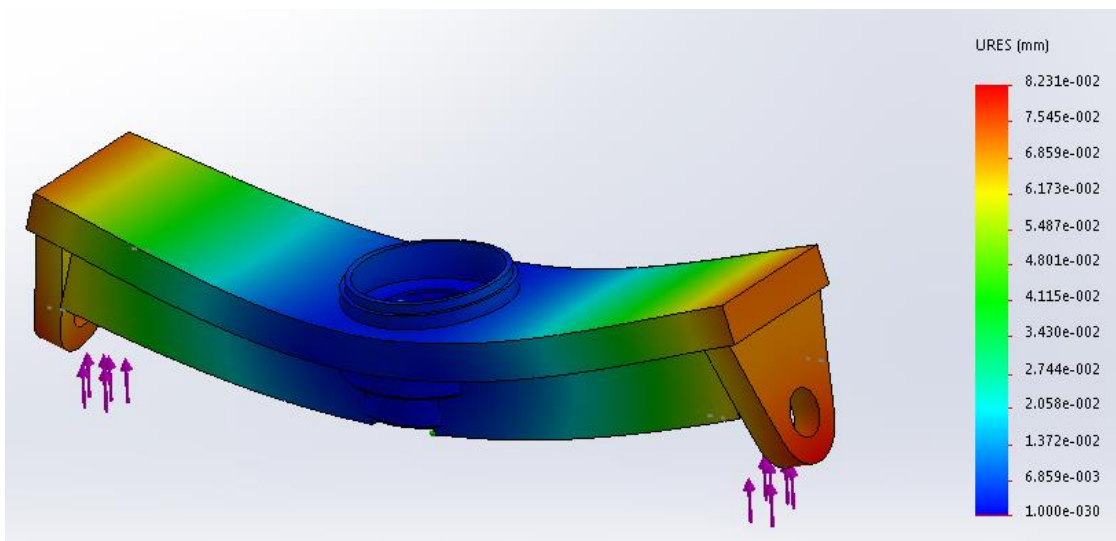

URES (mm)

8.231e-002
7.545e-002
6.859e-002
6.173e-002
5.487e-002
4.801e-002
4.115e-002
3.430e-002
2.744e-002
2.058e-002
1.372e-002
6.859e-003
1.000e-030

Fig.4.12: Displacement graph for Basis

Fig 4.13 shows Strain analysis for the Basis. It displays strain of different place on the part. The section in red has the highest level of strain, the blue section has lowest strain. Values corresponding to colors are indicated beside the spectrum.
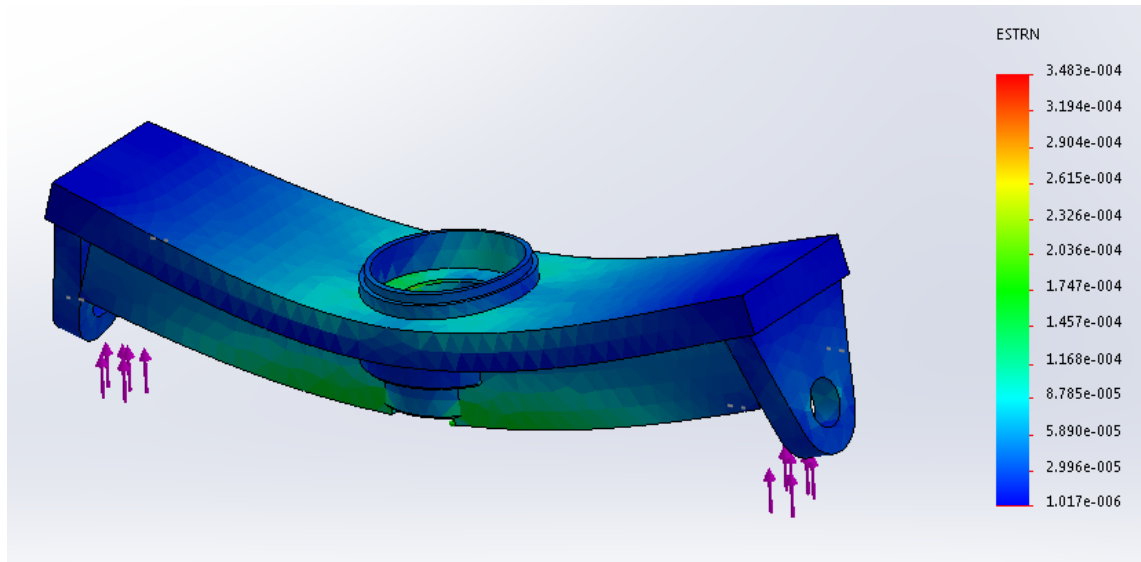

Fig.4.13: Strain diagram for Basis

Fig.4.14 shows factor of safety analysis of part Basis. Different color indicates different value of factor of safety accoridng to the specturm on the right side. The minimum factor of safety is 2.029e+000, where the maximum is up to 3.898e+003.
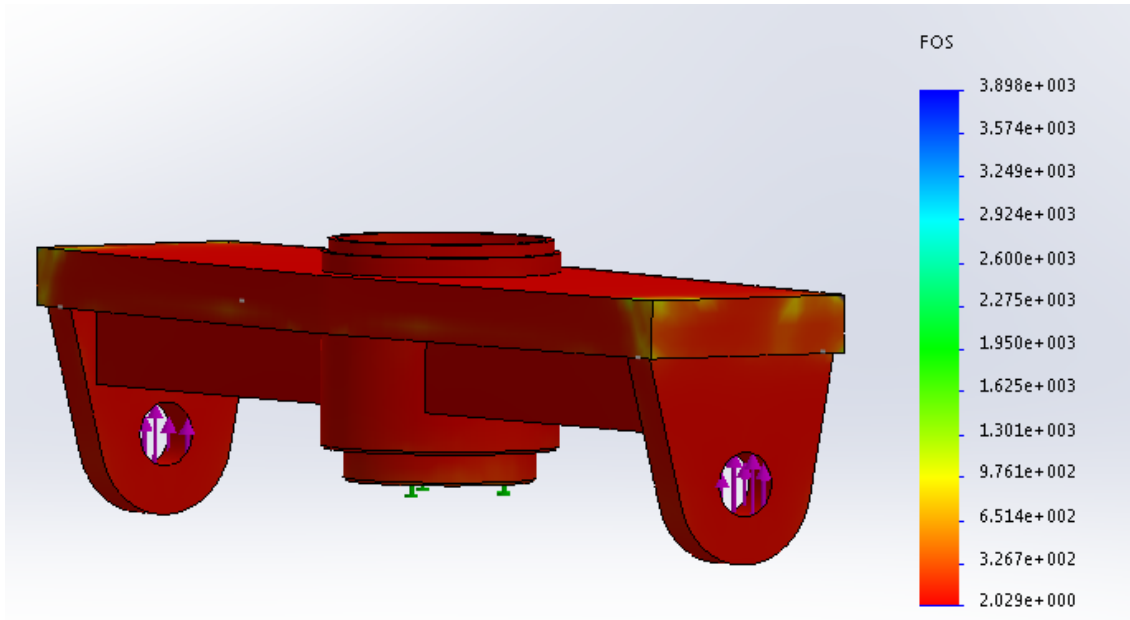
Fig 4.14: Factor of Safety plot for Basis

Fig 4.15 shows options and result of optimization for the basis. Thickness1" and "Thickness 2" are names of the two variables. They are constrained in a range between Min and Max value. Constraint for this optimization is Minimum Factor of Safety should be over 2. Object is set to minimize mass of the part. There are 12 scenarios for this analysis, and groups in red are not feasible design, the green one is our optimal result.

Fig.4.15: Variable View of Optimization for Basis

		Current	Initial	Optimal (6)	Scenario 1	Scenario 2	Scenario 3
Thickness 1		18mm	18mm	18mm	16mm	18mm	20mm
Thickness 2		26mm	26mm	24mm	22mm	22mm	22mm
Minimum Factor of Safety1	> 2.000000	2.190642	2.190642	2.029355	1.715092	1.849447	2.202280
Mass1	Minimize	6218.4 g	6218.4 g	6145 g	5707.69 g	6071.6 g	6435.52 g

Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11	Scenario 12
22mm	16mm	18mm	20mm	22mm	16mm	18mm	20mm	22mm
22mm	24mm	24mm	24mm	24mm	26mm	26mm	26mm	26mm
2.368429	1.864636	2.029355	2.239634	2.530333	1.972709	2.190642	2.467023	2.736533
6799.43 g	5781.09 g	6145 g	6508.92 g	6872.83 g	5854.48 g	6218.4 g	6582.31 g	6946.23 g

Fig.4.16: Result of Optimization for Basis

Model Based Definition (MBD) Results for the Basis:

Figures 4.17, 4.18, 4.19, and 4.20 show different views of the Basis developed as part of the Model-based definition of the part. Figure 4.21 show the 3D pdf document generated by the Solidworks MBD module.
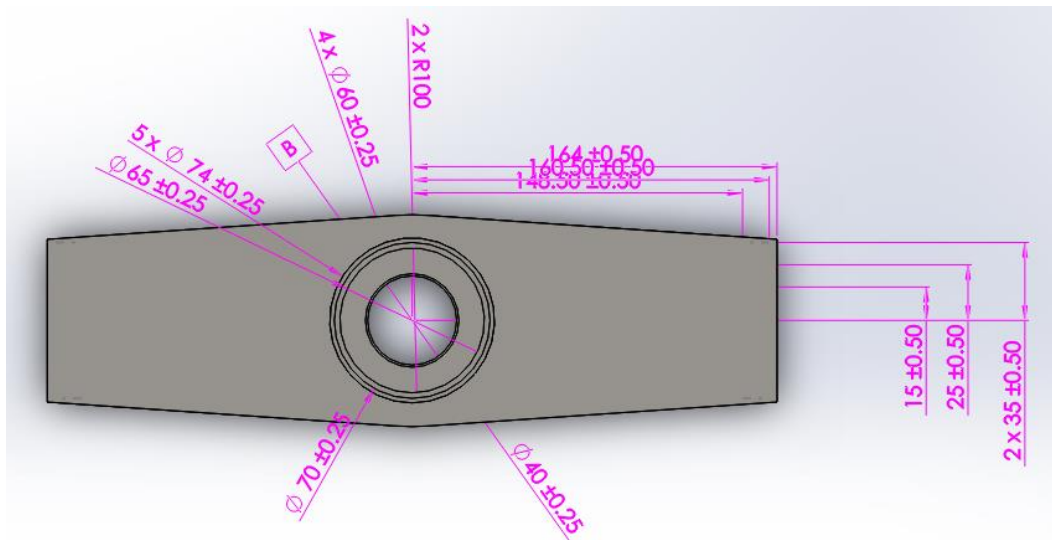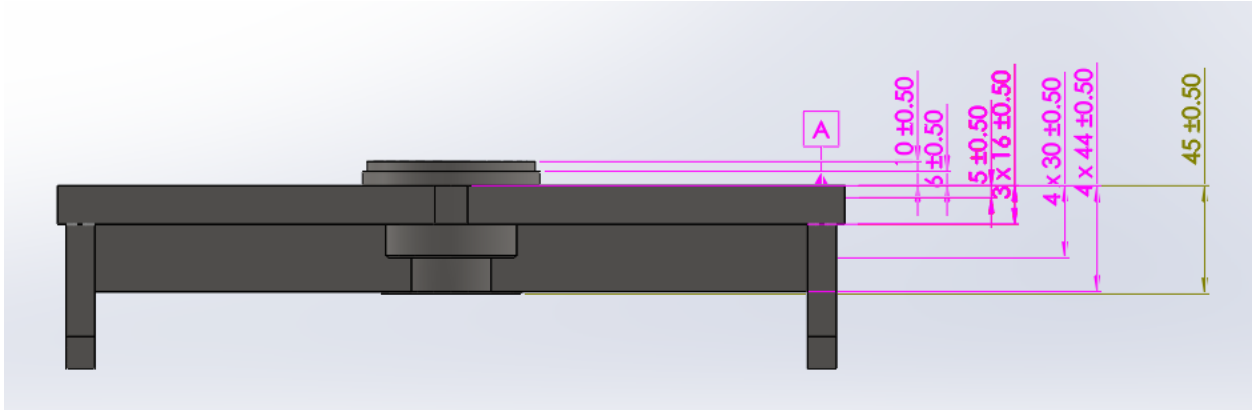

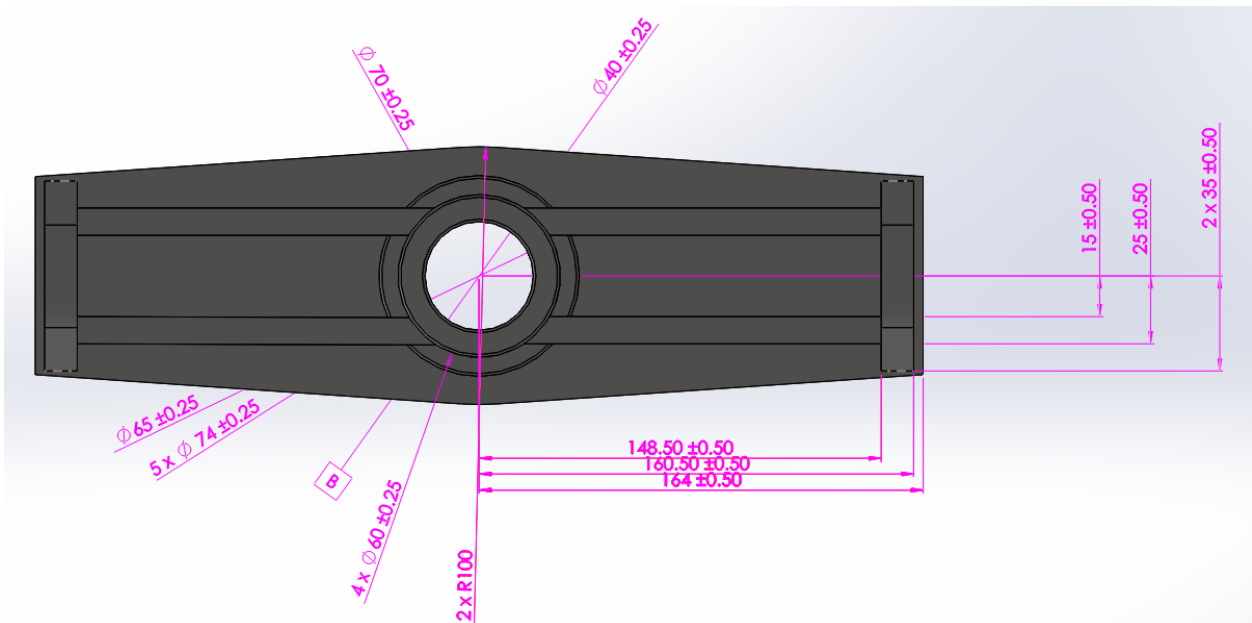Fig.4.17: Top View of the Basis

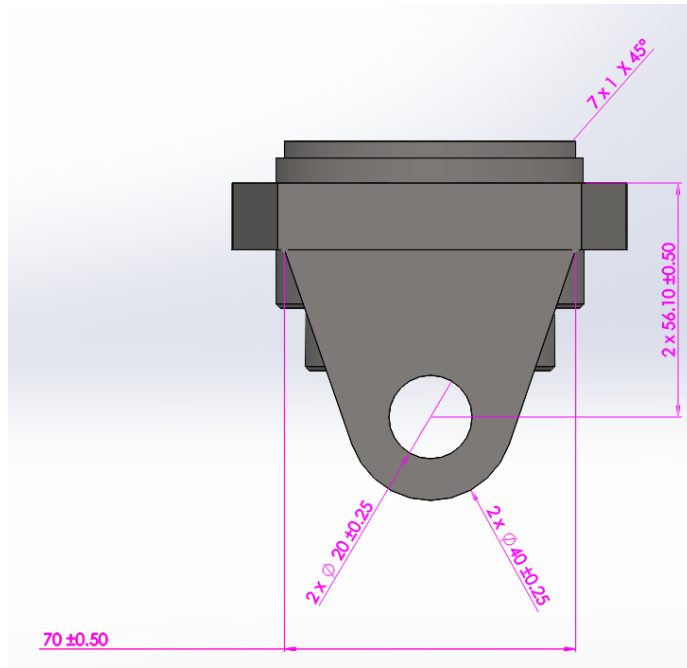Fig.4.18: Front View of the Basis

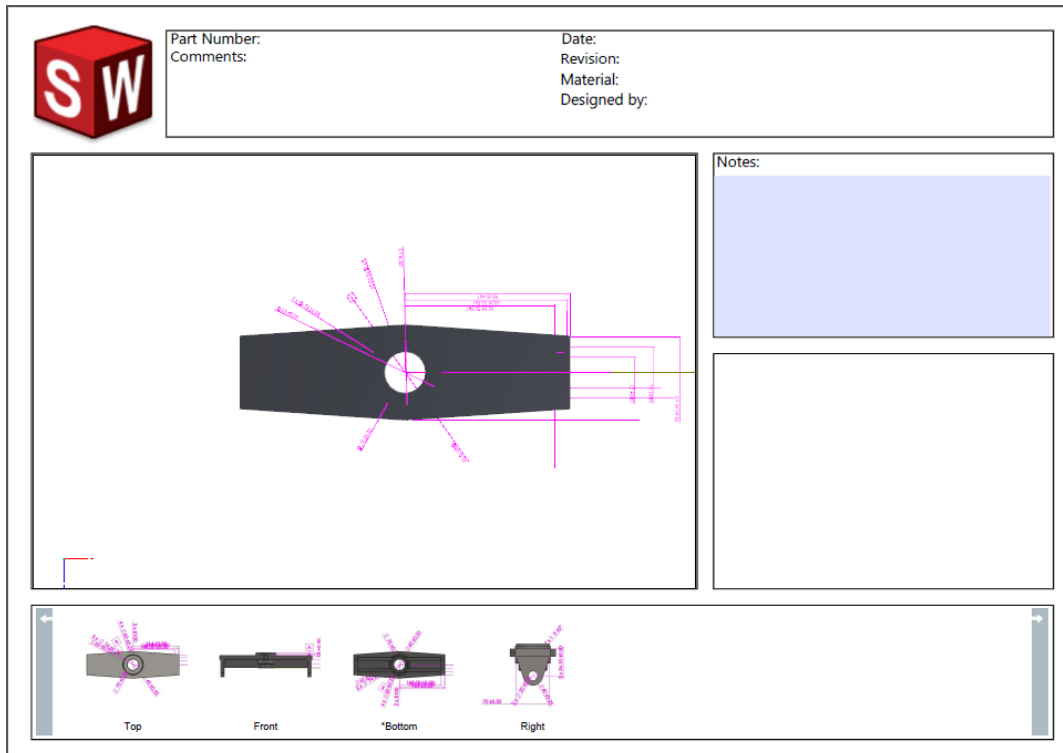Fig.4.19: Bottom View of the Basis

Fig.4.20: Right View of the Basis

Fig.4.21: 3D MBD PDF of the Basis

4.3 Concluding Thoughts and Future Research

Traditional design process is a sequential approach in nature, modules of it get separated from each other in the industry practice, and it means the different tasks are conducted at different times and using different software packages on different workstations. It constrains people to carry out engineering design in only one direction on one path. When any problem is found anywhere in the process, engineer has to go back to the beginning to redo his design to make some change.

Compared with it, the integrated approach studied in this paper provides engineers an absolutely flexible solution to implement engineering design, which has unified data structure and a comprehensive mapping of parameters (geometrical, technological, etc.). Data standardization allows repetitive tasks and data updating to be automated. CAD modeling, design optimization and model based definition will be built based on a single data source. Engineers don't need to spend time on creating different files and worry about the format inconformity of files.

Besides, the integrated process allows engineers to make changes anytime during their design and they will see the difference result caused by the changes immediately. It helps them to compare alternative design plans and choose the one that performs best.

In the future, integrated approach could be able to contain the manufacturing disciplines, the use of 3D models as comprehensive product/process data repository speeds up simulation tasks and makes them more controlled. (Alemanni M, Destefanis F, Vezzetti E., 2011) Computer-aided technologies (CAx) application can provide a more comprehensive set of data, allowing better integration and task automation.

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