Design and Testing of a Field-Testing Unit for Agricultural Soil-Engaging Tools

BY

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A Thesis

Submitted to the Faculty of Graduate Studies

In Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

Department of Mechanical Engineering

University of Manitoba

Winnipeg, Manitoba

Abstract

Tillage and seeding, the physical manipulation or disturbance of the soil for crop production, are important aspects of agriculture. Over the ages, farmers have relied on agricultural machinery and tools to improve crop productivity and agriculture sustainability. New and efficient agricultural machines are developed and tested frequently to satisfy the ongoing demand for crop production. Tillage and seeding play an important role in modern day crop production. However, field testing units specifically built for evaluating different tillage and seeding tools (named as soil-engaging tools) are not available. Therefore, the main objective of this research was to develop a field-testing unit to test soil-engaging tools for agriculture. The field-testing unit is designed to have the following specifications: capable of traveling on highways; versatile for mounting different soil-engaging tools; adjustable toolbar gang angle (0 to 22º) and tool working depth (1-16 in). The major mechanical components of the testing unit include a mainframe, subframe, rocker arm, two transportation wheels, and a hydraulic system. The testing unit is also designed to equip electronic instruments, such as a dynamometer, laser profilers, and high-speed cameras to monitor soil dynamic properties. The field-testing unit is designed, manufactured and tested for the operating conditions and feasibility of selected tools. Results showed that the field-testing unit generally met the design specifications.

Acknowledgement

I would like to sincerely thank my advisor, Dr. Qingjin Peng, for his valuable academic supports throughout my whole master program. I would like to thank Dr. Ying Chen, for supporting me financially and academically throughout my master's programme. I would like to thank NSERC Strategic Project Grants and Small Research Equipment Funding Program (SREF) of University of Manitoba for their financial support.

I would like to thank the industrial partners for this research, Bhuler Versatile Inc. Winnipeg, and Atom-jet Industries, Brandon, for their advice throughout the research, and Agriculture and Agri-Food Canada Research Farm at Portage La Prairie, Manitoba for providing tractor and field for the field tests. I would like to thank Dr. Tessier Sylvio, for guiding me in the field of CAD and manufacturing. I would also like to thank all the students wholeheartedly who guided and helped me with the field tests.

This thesis is dedicated to my parents, and loving sister.

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Chapter 1 General introduction

1.1 Introduction

Agricultural soil-engaging tools play an important role in maintaining soil health, soil tilth and prevent water runoff on the surface of the soil. There are many types of soil-engaging tools, such as tillage tools and seeding tools. Tillage tools are main soil-engaging tools, and therefore, most discussion in this thesis is around tillage tools. Various research has been conducted in designing numerous tillage tools in the past. However, testing of tillage tools in the field remains as one of the major challenges due to implements available for testing on the field. Tillage tools have been studied and analyzed to design better tools for efficient crop production. As tillage tools are operated in soil, understanding of soil-tool interaction plays an important role in modern day tool designs. Testing agricultural tools for force exerted and other parameters at different field conditions help in designing an efficient tool. Forces acting on the tool can be multidirectional, and they are draft forces (horizontal forces), vertical forces, and lateral forces. The direction of vertical force can be upwards or downwards, depending on the type of soil-engaging tools. Shank-type tools, such as subsoilers and cultivators, typically have downward vertical forces, which helps maintaining the working depth. Disc-type tools, such as rotary vertical tillage tools, typically have upward vertical force, which try to pull the tools out of the soil. Soil-bin testing has been the most common form of agricultural tool testing for these forces.

Many researchers have done considerable amount of work on soil-bin design (Godwin et al. 1980). In the 1980's, the soil processing devices were designed by few researchers (Kohn et al. 1997). The soil bin instrumentation was focused largely in late 20th century (Gu, 2002). Most research and development were done on the soil bin in the past century. It was found from literature that some of the disadvantages of the soil bin include low operating speed, limit in maximum loads, missing the existence of vegetation and crop residue, limitation on different soil condition and lengthy test durations (Gebregziabher et al. 2013; Muhammed et al. 2017). There are many types of soil in Canada (Earle, 2008). Hence it is certainly not sufficient to test soil-engaging tools in soil-bins using a single type of the soil. There is a need for field testing of soil-engaging tools to overcome all the limitations of the soil-bin and test soil-engaging tools in different soil conditions in fields. This helps in designing effective and efficient soil-engaging tools for modern day crop production.

1.2. Objectives and scope of the research

Although many research activities have been done on soil-tool interaction using methods such as soil-bin testing and FEM analysis, there is not enough work done in the actual field conditions due to the limitations of lab test equipment.

This research aims to contribute to the development of agricultural soil-engaging tool testing by designing a field-testing unit to work in different field conditions for a vast variety of agricultural tools. This thesis demonstrates the full prosses of machine design involving design, development, and testing of the field-testing unit. The specific objectives to achieve this main goal are identified as follows:

- Research follows design methodology to determine design requirements, chooses the design and test solutions in the development of an efficient field-testing unit.
- Design solutions will be verified by using the force analysis on the machine. The designed machine will be manufactured and verified for its functionality. Additionally, specific soil-engaging tools, seed openers will be tested using the

field-testing unit and data will be collected to determine the performance of both the field-testing unit and the openers.

1.3 Research methodology

Different types of tillage tools and test equipment's are studied to determine requirements of the field-testing unit. Methods that are conventionally used to predict soil-tool interaction are reviewed along with different types of agricultural tools. Draft forces are calculated for common tillage tools to determine the load acting on the field-testing unit. Advantages and disadvantages of each approach are discussed.

Generic machine design methodology is used in this research to determine the machine requirements, evaluate the solutions, and develop prototype solutions. Commercial agricultural machines from different equipment manufacturers are studied to establish an outline of the machine to be designed. Design tools such as Solid works, Inventor, Ansys, and AutoCAD are used for the design and analysis of the machine. Also, the analytical approach is used for the calculation of forces involved during the field operation. Draft forces are calculated for considered soil-engaging tools to determine the load exerted on the machine frame.

Field study of the manufactured field-testing unit is used to verify the working parameters and performance of the field-testing unit. Seed openers are tested in actual field conditions with depths of 0.5, 1.0, 1.5 and 2.0 inches at speed of 10 km\h. Field data such as depth achieved, soil coverage, soil profile and data regarding soil conditions are recorded and analysed.

1.4 Thesis outline

This thesis is organized into six chapters. Chapter 1 is the introduction section. Chapter 2 covers literature review of different tillage tools and approaches that are used to study the soil-tool interaction. Advantages and limitations of the approach are discussed. Chapter 3 covers the methodology used in this study, including HoQ (House of Quality) and design requirements. The criteria for evaluation of general parameters are defined, and parts for the field-testing unit are selected. Chapter 4 describes the analysis process of the machine, including meshing, constrains assignment, applied force, and analysis results. Chapter 5 consists of detailed field testing of the unit with openers and validation of the field data. Safe operating procedure and circle check of the field-testing unit are also discussed. Chapter 6 discusses the conclusion and recommendation for the research.

Chapter 2 Literature review

2.1 Types of tillage

There are different types of tillage methods used for cultivation. Tillage methods can vary based on different tools used, number of passes and percentage residue in the field. Tillage can also be differentiated based on field residue as conventional tillage, conservation tillage, and zero tillage.

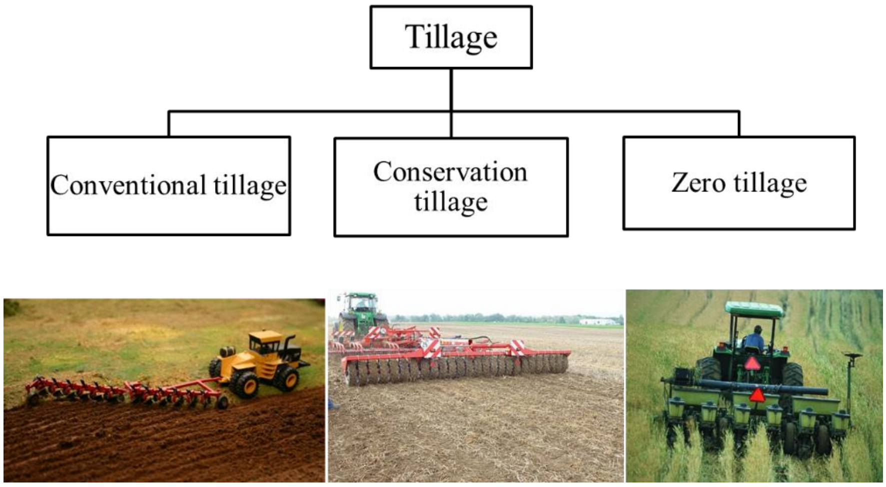


Figure 2.1 Types of tillage

Figure 2.1 shows the different types of tillage operations. Conventional tillage generally involves a primary pass using heavy tillage tool to loosen soil and mix all the materials (fertilizers, residue, weeds, etc.). The primary pass is followed by additional passes to create the seedbed. Generally, in conventional tillage, 0 to 10 % of the residue is left on the field. Some of advantages of the conventional tillage include low quantities of pesticide application, few chances of early weed growth and elimination of residue from the previous harvest. Some of disadvantages are that there will be high compaction of the soil due to more passes in the field, reduction in soil moisture due to high soil disturbance, high fuel cost per acre and the method is time-consuming (Tiessen et al. 2010).

Conservation tillage conserves soil, water, and energy resources by reducing the tillage intensity and retaining some part of crop residue as a means of fertilizer for the next crop. Advantages of the conservation tillage include the minimum soil erosion, increased fertility and yield, reduced fuel consumption and soil compaction due to reduced tillage (Afzalinia et al. 2011).

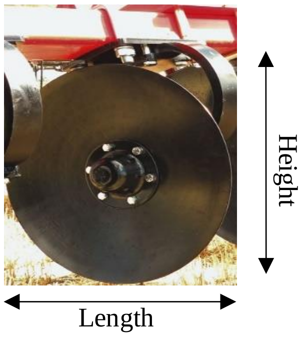
In zero tillage or No-till, all the residues from the previous crop are left on the field. The process helps in retention of organic matter and circulation of nutrients. Advantages of the zero tillage include a large amount of reduction in the fuel consumption and labor (Ibendahl, 2016).

2.2 Choice of tools

Tillage tools are the heart of agriculture. Different types of tools have been used from the beginning of the time to cultivate, harvest and produce efficient crops. Some of the common types of tools include plows, disks, cultivators, sweep, openers, and subsoilers (Das et al. 2006). To create an efficient testing unit for testing soil-engaging tools, preliminary knowledge of different tools and their dimensions are necessary. Table 2.1 shows the dimensions and description of common tillage tools. The height of the tool is defined as the distance between bottom tip of the tool to the mounting point, and the length of the tool is defined as distance between front tip of the tool (travel direction) to rear end of the tool (travel direction). Data were obtained from brochures of tool manufacturing companies and visiting commercial dealerships to record the dimensions.

Implements like cultivator, discs, sweep and seed openers are used for field operations at shallow depths. Other tools like deep tillage tools and subsoilers are used at much greater depths to loose subsoil. Both tillage depth and the tool dimension data help in determining the operating depth of the testing unit to be manufactured.

Table 2.1 Dimensions and features of considered tillage tools

Tool	Dimension	Features
a) Disk 	Height: 25 – 33 inches Length: 25 – 30 inches	• Used to cut residues into smaller pieces and mix them with the soil. • Used in vertical tillage. • Different disk shapes and sizes available.
b) Hoe opener 	Height: 28 – 30 inches Length: 20 – 25 inches	• Common type of tool used for seeding. • Used to open the soil and incorporate the seed. • Used in distribution of fertilizers with the seeds.
c) Cultivator 	Height: 15 – 20 inches Length: 15 – 20 inches	• Used to loosen and pulverize the soil. • Used in seedbed preparation. • Produce high soil disturbance.
d) Subsoiler 	Height: 25 – 35 inches Length: 20 – 26 inches	• Used for deep tillage. • Can be tractor mounted or pull type. • Used to break up hardened soil where cultivator and other tools cannot be used.

2.3 Tool testing methods

The testing of soil engaging tool provides vital information regarding the performance and evaluation of newly developed implements. This information can be further processed to manufacture improved soil engaging tools. It was found in literature that many research methods have been used to study soil engaging tools. Studying the effect on the soil profile and other parameters after the soil-tool interaction is key in finding the overal performance of the tool. Figure 2.2 shows different methods used to study soil engaging tools and their applications.

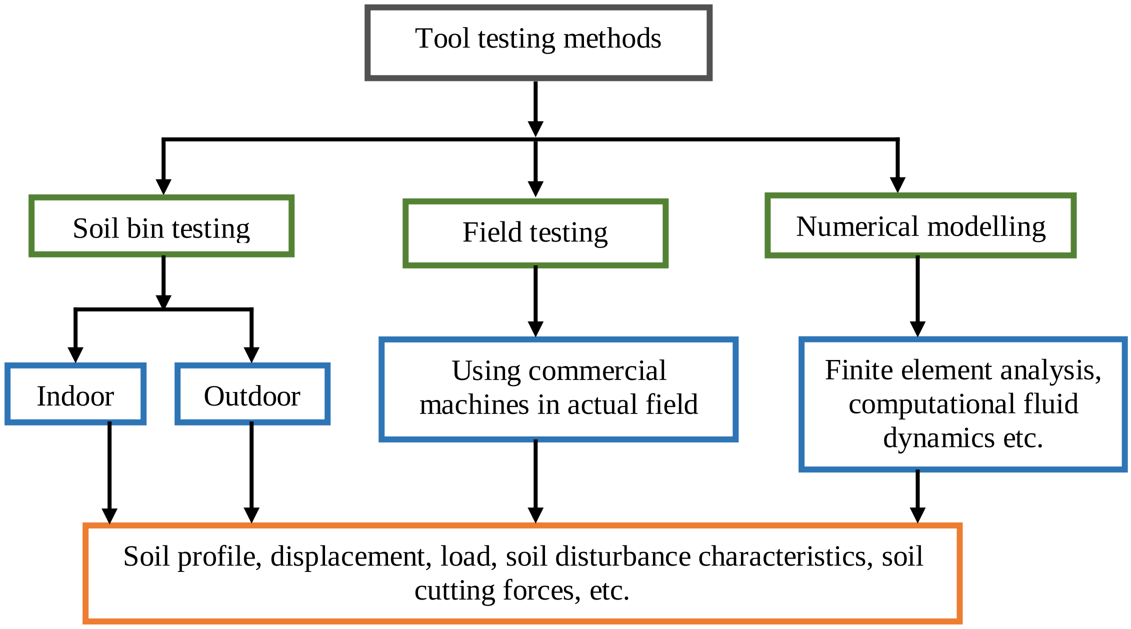


Figure 2.2 Tool testing methods and applications

Soil bin is one of the most common facility used to study soil engaging tools. Many researchers have worked in this field to make soil bin studies more realistic and efficient for testing tools in a confined environment (Muhammed et al. 2017; Chen et al. 2018; Godwin et al. 1980). Figure 2.3 shows one such setup located at the Soil Dynamics and Machinery Lab, University of Manitoba, Winnipeg, Canada. Soil bins are one of the fastest and efficient ways to test soil engaging tools in a controlled environment. Recently, Chung et al. (2008)

conducted a soil bin study to verify the performance of an on-the-go soil strength profile sensor. The sensor was tested at different depths in the soil bin to determine the maximum field data collection speed.

A soil bin consists of soil, which is manually constructed based on the desired test criteria. The setup uses an electric motor driven a mechanical device (soil bin carriage) on which testing tool is attached. The bin is filled with soil and can be compacted using compactor or roller to simulate the compaction level of field soil. Crops are also grown inside the bin in some cases to simulate field-like experiments. The tests conducted in soil bin are low-speed tests due to the limitation in space and the ability of the machine to travel at a high speed. To overcome this constraint on the soil bin, high-speed field tests are conducted to examine the interaction of tools with soil.

a) b

Figure 2.3 a) soil bin setup b) subsoiler tool attached to the soil bin carriage

Other than soil bin experiments, field testing of soil engaging tools is performed to determine the efficiency of the soil engaging tools in the actual field. Field testing provides accurate data on how the tool will interact with soil in field conditions. Unlike the soil bin, there is no need for artificial preparation of the soil bed as the field condition replicates the real-life situation. Much research has been published on results and findings of the soil-tool interaction conducted in field setups (Zeng, 2019; Li, 2006; Vaisman 2010; Chen et al. 2016.). Field testing is conducted by mounting the machine on a pull type device like trailers or mounted directly on tractor's three-point hitch. The existing commercial machines can only be used for a limited number of tools and limited operating depths (2-5 inches), which limits the type of tools used and performance tested. In the ongoing research, the tools are mounted on a commercially available machine with modifications or a custom manufactured machine frame to facilitate the considered tools. Figure 2.4 shows a setup where a tillage tool (rippled disc) is tested on a commercially available frame (Zeng 2019).

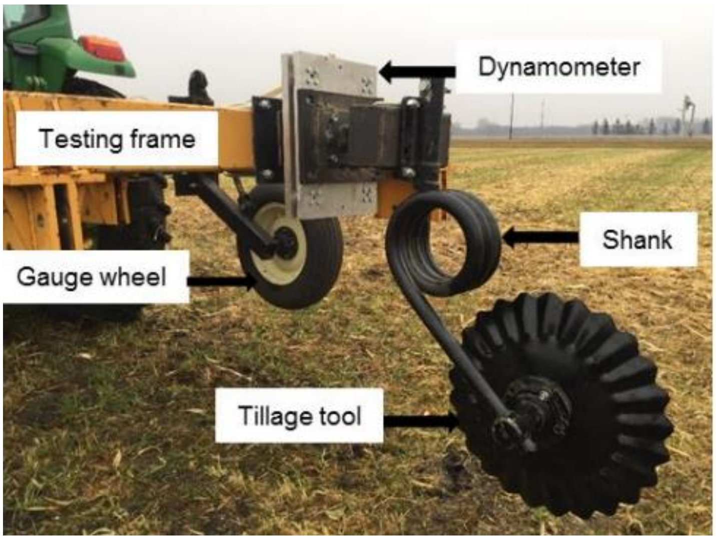


Figure 2.4 Tillage tool being tested on commercially available frame (Zeng, 2019)

Numerical modeling methods such as the finite element analysis (FEA), computational fluid dynamics (CFD) and discrete element modeling (DEM) are also used to study the interaction between soil and tool. Recently, Chen et al. (2018) used the DEM to simulate the soil cutting forces acting on a disc opener. Many researchers have worked in the field of FEA and DEM to predict soil cutting forces and other parameters, such as soil disturbance characteristics, during soil-tool interactions (Coetzee, 2014; Tekeste, 2015; Ucgul et al. 2015). New and improved particle flow codes in software like Ansys and PFC allow users to create three-dimensional particles. These codes help in analyzing the tool within the soil-like environment. There is no research reported specifically on the development of a field-testing unit to test different agricultural tools in a single machine. Also, the field-testing proves to be the efficient method for testing agricultural tools by overcoming all the limitations of other methods. This proves to be the key factor for the development of a field-testing unit.

Table 2.2 Summary of literature on tillage tools testing methods.

Method	Literature	Comments
Soil bin tests	(Muhammed et al. 2017; Zeng, 2019; Vaisman, 2010; McLaughlin et al. 2006; Mardani et al. 2010)	-Soil tool interaction tested, and parameters recorded using soil bin. -Limit in test length and operating depths. -Lower operating speed of 5-10 km/h.
Field experiments	(Zeng, 2019; Vaisman 2010; Chen et al. 2016)	-Using commercially available machines or modified testing rigs. -Limit in testing multiple tools. simultaneously. -Modifications necessary depending on the types of testing tool.
Numerical modelling	(Muhammed et el. 2018; Tekeste, 2015; Ucgul et al. 2015; Coetzee, 2014)	-Simulation of granular materials (soil, stone) with soil engaging tools using DEM to find soil profile and other parameters related to soil-tool interaction. -High licensing cost of software. Requiring testing data to validate the models.

The disadvantage is the model inaccuracy due to the empirical assumption of parameters during simulation. Also, the licensing for the software is highly priced, which limits the number of users. Table 2.2 summarizes literature on different methods used in testing of tillage tools.

2.4 Machine design methods

Design methodology plays an important role in the efficient design of machines. The engineering design follows a series of steps like defining the problem, doing background research, specifying requirements, finding solutions, prototyping solutions, testing, and redesigning. In the engineering design process models, there are numerous design methods that can be applied in developing prototypes. Many design methods in use are originated in the 1960's and 1970's to modern day design practices. Recently, Lee et al. (2001) discusses the relationship of design rules and requirements used to build design house of quality (HoQ). Haik et al. (2018) described different techniques and methods used in manufacturing industries to select appropriate methods for new product design. Analysis methods were also studied by Russell, (2013) and Gao et al. (2011) in determining the stress and deformation for verifying the strength of structural components.

A literature review was conducted to establish a basic idea on design and analysis steps followed in machine design by different researchers. The review helps in selecting methods and principles for the development of the field-testing unit in this study. Table 2.3 summarizes literature based on various design methodologies. Based on the summarization of the literature review presented. Customer data, market survey, and HoQ were used to determine requirements for the initial prototyping stage of the machine. CAD modeling software like SolidWorks, Autodesk Inventor and Pro-E are essential in the development of a successful product design. Also, modern simulation software tools like Ansys, Autodesk robot and SolidWorks simulation were used to verify the structural strength of the CAD model.

Table 2.3 Summary of literature on design methodologies.

Literature	Method/Process	Findings
(Feng, 2013)	- Quality function development and Kano model	- Good overall performance and customer satisfaction.
(Phadnis, Mulay, and Bhujbal 2016)	- Market survey - Modeling and analysis in Hyper mesh-Ansys.	- Problem statement was derived from the survey. - Design and analysis of plow tool.
(Ahmad et al. 2018)	- CAD model using solid works and simulation. - Design methodology.	- Evaluation of cutting force acting on the tool. - Comparison of available tools for the design process.
(Stevenson, Dooley, and Anderson 1994)	- Design principles - Market research - Feedback systems	- Comparison of different design process and methodologies. - Use of design practices in outsourced manufacturing companies
(Gebregziabher et al. 2007)	- Mathematical descriptions(traditional force analysis) on static analysis of structure. - Finite element (FE) analysis using ABAQUS package.	- Design guidelines for small-scale tillage implements. - Experience and trial- error method.

In this research, customer requirements were decided by a series of interviews and observations. Based on obtained requirements and market research, a HoQ was finalized.

General design methodology, as described by Ulrich and Eppinger (2012), was used for the machine design. A comparison of commercially available machines was made to study the structures and features of the available tillage machines. CAD modeling software - SolidWorks was used for the design. Ansys and Autodesk Robot were used for the structural analysis of the CAD model.

Chapter 3 Design of field testing-unit

3.1 Functional requirements

Functional requirements of the design were decided based on customer requirements. Data gathered through interviews, observations, and discussions with participating companies were interpreted in terms of customer needs and further converted into functional requirements. The obtained functional requirements were organized based on their importance. Table 3.1 shows the importance rate of functional requirements. The importance rate was determined by conducting group discussions with the project team and participating companies. This information led to a common understanding of the target environment, as well as various functional requirements. The listed functional requirements will be used for conceptual design.

Table 3.1 Functional requirements and importance rate

No.	Functional requirement	Importance rate
1	Supporting variable tool length	5
2	High travel speeds (up to 80 km/h)	3
3	Working in high residue conditions	5
4	Highway transportation	4
5	Safety during transportation	3
6	Tool perpendicular to the ground	4
7	Tool gang angle flexibility	3
8	Having ballast holders	2
9	Different working depths	5
10	Parking stability	3
11	Operation with hydraulic cylinders	4

The obtained functional requirements include the support variable tool length, travel at high speeds and other functional requirements, as shown in Table 3.1. Their importance is rated between 1 to 5; 1 being the lowest while 5 being the highest. Furthermore, the functional requirements were converted into technical specifications. For example, functional requirement 1 is related to the tool length and tool mount type. By determining the appropriate length and mount size of tools, functional requirement 1 can be satisfied in the design. Table 3.2 shows the relationship between functional requirements and technical specifications. The obtained relationship is further analyzed, using house of quality (HoQ) to determine absolute and relative scores.

Table 3.2 Relation of technical specification and functional requirements

No.	Functional requirement No.	Technical specification	Unit
1	1,3	Adjustable frame height	in
2	3,5	High ground clearance	in
3	4	Maximum machine width	m
4	9	Increased weight of the frame	kg
5	11	Number of hydraulic couplers	list
6	1	Adjustable toolbar height	in
7	5	Blunt edges in the frame (no sharp edges)	mm
8	4,5	Frame locking mechanism	list
9	1,9	Maximum stroke of hydraulic cylinders	in
10	6	Toolbar parallel to frame	deg^{o}
11	4,5	Safety lights	list
12	2,4	Wheel size (26,29,32)	list
13	8	Maximum ballast weight	kg
14	10	Trailer jack	list
15	7	Adjustable toolbar angle	deg

3.1.1 House of quality

House of quality (HoQ) is used to determine the priority of technical specifications for function requirements. Table 3.3 shows a HoQ developed using function requirements along the column and technical specifications along the rows. The roof of Table 3.3 consists of a correlation matrix of technical specifications. The correlation matrix identifies conflicts of different technical specifications to meet one function requirement. The matrix is rated as strong relation, medium relation, week relation, no relation and contradiction. The obtained relationship matrix is used to compare design solutions for an improvement or to avoid any contradiction. The relationship between functional requirements and technical specifications are marked as strong, medium and weak. The absolute weights and relative scores in the table are calculated by following formulas:

$$W_j = \sum_{i=1}^{n} a_{ij}\ d_i \qquad (3.1)$$

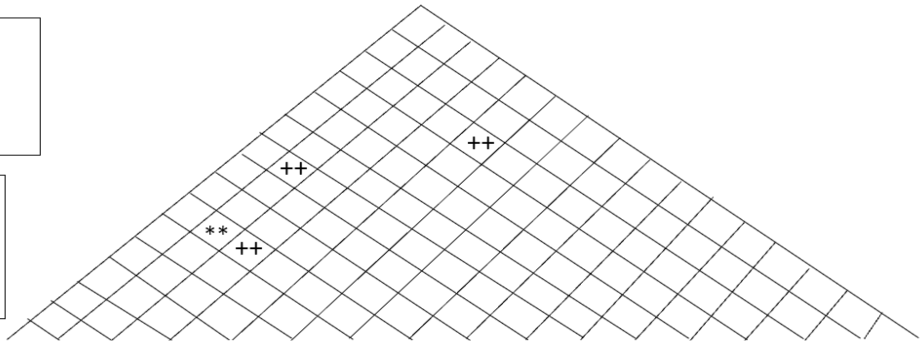
$$r_j = w_j \Big/ \sum_{i=1}^{m} w_j \qquad (3.2)$$

where, W_j is the absolute weight of each function, a_{ij} is the relationship value about functional requirements and technical specifications, d_i is the importance of i_{th} functional requirement, and r_j is the relative weight of each function. The absolute weight is calculated by the importance value of related functional requirement and technical specification. For example, by using the adjustable frame height (Technical specification 1), the machine can support variable tool lengths (Functional requirement 1). Similarly, other technical specifications can also contribute to the importance value of functional requirements, as shown in Table 3.3. Thus, the weight of technical specification (1) in the HoQ is (5×5) + (5×5) = 50. The absolute weights of other technical requirements are similarly calculated to determine relative scores.

Table 3.3 House of quality for functional requirements and technical specifications

Correlation matrix: roof
******: contradiction
+ +: Strong relation

Relationship matrix
S: Strong=5
M: Medium=3
W: Weak=1



Technical specifications / Functional requirements	**Importance Rating**	1. Adjustable frame height	2. High ground clearance	3. Maximum machine width	4. Increased weight of the frame	5. No. of hydraulic couplers	6. Adjustable toolbar height	7. Blunt edges in frame	8. Frame locking mechanism	9. Max stroke of cylinder	10. Toolbar parallel to frame	11. Safety lights	12. Wheel size (26,29,32)	13. Maximum ballast weight	14. Trailer jack	15. Adjustable toolbar angle
1. Support variable tool length	5	S					S			M						
2. Travel at high speed	3												S			
3. Work in high residue conditions	5	S	S													
4. Highway transportation	4			S					M			S	M			
5. Safety during transportation	3		M					S	S			S				
6. Tool perpendicular to ground	4										S					
7. Gang angle flexibility	3															S
8. Ballast holders	2													S		
9. Different work depths	5				M					S						
10. Parking stability	3														S	
11. Operate with hydraulic cylinder	4					S										
Absolute weight		50	34	20	15	20	25	15	27	35	20	35	27	10	15	15
Relative score %		14	9	6	4	6	7	4	7	9	6	9	7	3	4	4

The relative score is calculated by using obtained absolute weights. For example, the relative score to technical specification (1) is (50/368) × 100 = 14%. After obtaining the relative score for each technical specification, the score is arranged in descending order of importance to provide the design priority. In addition, design parameters are established for technical specifications, and the parameters are used in the generation of machine concepts.

3.2 Technical comparisons of commercial machines

Technical aspects and features of commercially available tillage machines were used for the concept design and selection of concepts. The data were obtained by field observations, review on machines from different manufacturers, interviews and discussions with participating companies. This resulted in overall knowledge on the field and machine operations. Figure 3.1 shows the commercial tillage machines considered for understanding the operation and performance of the machines.

Machines from different companies like Versatile, John Deer, and Field King were studied for better understanding of the frame structure, working depth, supported tools, and other parameters of the tillage machine. John Deer VT17 series is one of the efficient small-scale tillage equipment, consisting of gang tools like disks and rollers. The height of the frame in this machine can be adjusted according to the operating depth using the manual pin and clip system. The gang angle of the toolbar can be adjusted up to 15 degrees. The machine is capable of travelling at a maximum speed of 10 km/h. Another similar tillage unit from Farm King has similar features with a fixed gang angle. The machine also features a rolling basket attached at rear end of the machine. The working parameters and feature summary of the selected machines are shown in Table A3.2 of the Appendix section.

a) Versatile offset disk model- TD650N

b) John-Deer VT 17 series

c) Field King FKEHDHH-26-24

Figure 3.1Commercial tillage machines selected for design references

Versatile's TD650N is one of the leading equipment in the agricultural industry, providing efficient tillage operations at higher operating speeds. The machine width measures 8.1 meters during operations and can work at speed up to 19 km/h. Hydraulic cylinders mounted on the unit help in adjusting the height of the machine. The machine features a floating type hitch to keep the machine horizontal to the ground and achieve an even tilling across the field. The machine also features FS-24 type tires which are recommended for farm and field use. The data and design knowledge obtained from the comparison helped in developing the concepts of the machine. Other information like the frame cross-section, tires used, hydraulic cylinders, and material used was collected for the selection of parameters in the conceptual design of the testing unit.

3.3 Concept generation and selection

Based on the HoQ, parameters and data obtained by comparison of commercial machines, two conceptual 3D models were proposed in two types, disk harrow type and vertical tillage type. Disk harrow type is used for small scale tillage, whereas vertical tillage type machines are used for large scale operations. Generally, commercial disk harrow machines have a single frame. Toolbars are directly attached to the mainframe and can be adjusted using a pin and clip system. Concept A, as shown in Figure 3.2, was based on the design of disk harrow machines. Vertical tillage machines are comparatively larger than disc harrow machines. They have two frames, mainframe and toolbar frame. The toolbar frame is attached below the mainframe with linkages or bolts directly connected to the mainframe. Concept B, as shown in Figure 3.3, was based on vertical tillage machines. Both concepts consist of a mainframe, hydraulic cylinders, hitch adjustments and transportation wheels.

Concept A is designed with four tool holders. Tools like VT disk, cultivators and openers can be easily attached to the tool holders with bolted mechanism. The subsoiler tool can only be mounted on the rear bar of the mainframe due to its large size. The hitch frame consists of two supports directly connected to the mainframe using pin and clip system. A spring-loaded drawbar also connected between mainframe and hitch frame to adjust the angle of the hitch manually similar to John deer’s VT 17 series. A single hydraulic system connected between wheel frame and mainframe allows the users to raise or lower the mainframe according to the required operating depth. Concept A only allows smaller gangs

(20 – 36 inch) to be mounted on the tool holders due to its limited size. Figure 3.2 shows the Concept A with hitch adjustment, tool holders, and hydraulic cylinder.

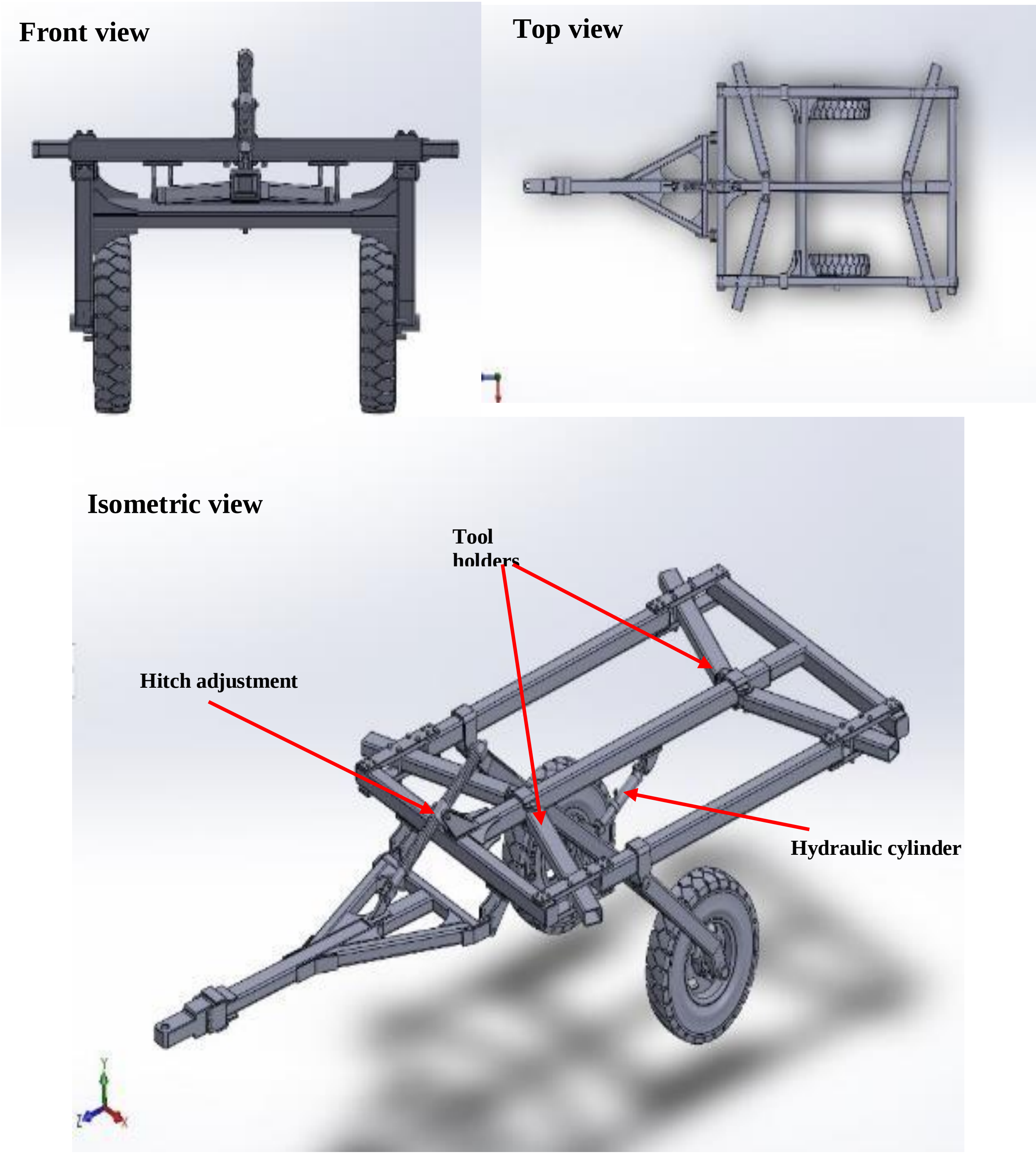


Figure 3.2 Field-testing unit concept A

The complete list of components used in the design of field-testing (Concept A) unit is show in Figure 3.3. The parts are divided into nine major components, and the numbered description of the components are shown in A3. 1.

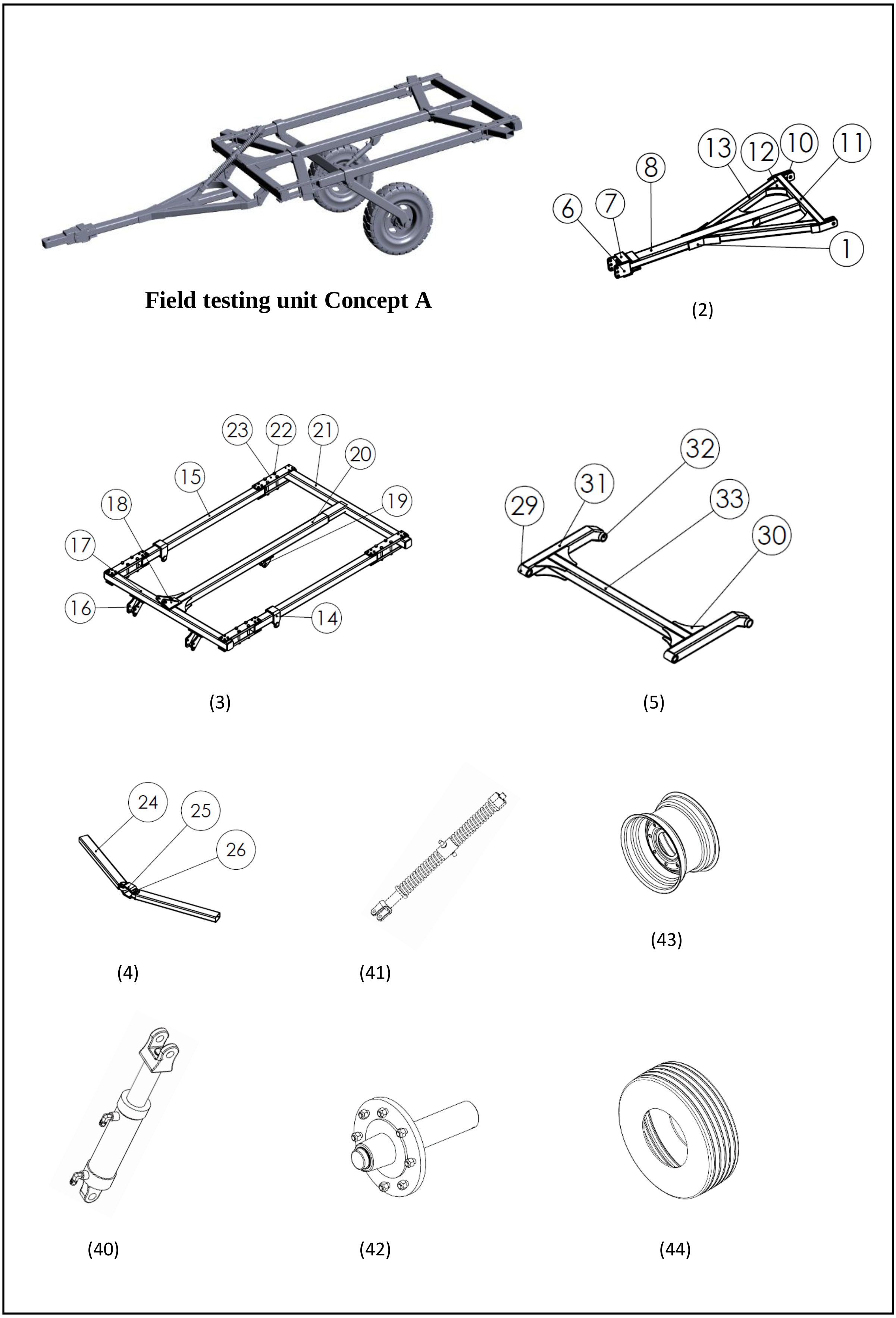


Figure 3.3 Components of the Field-testing unit (Concept A)

Concept B consists of two frames, a mainframe and a sub-frame. Figure 3.4 shows the field-testing unit concept B. Mainframe acts as a base to hold all the other child parts of the assembly. The subframe consists of two toolbars (tool holders); they are attached with pins on one side and bolted on the other side. The toolbar is designed to accommodate all the considered tools (opener, subsoiler, and VT disk). The mainframe consists of three hydraulic cylinders. The first cylinder is attached to the hitch and mainframe (adjust hitch height), the second cylinder connects the mainframe and subframe (for controlling the height of the subframe), and the last cylinder connects mainframe and rocker arm (allows to change height of the mainframe).

There are 44 components in the assembly of the field-testing unit (Concept B). the components of the field-testing unit are shown in Figure 3.5, and a complete list of components is shown in Table 3.4. The mainframe and subframe are connected with two individual linkages on both sides. The linkages assist in keeping the subframe parallel to the mainframe. The rocker arm is directly connected to the mainframe with a heavy-duty Plummer block, which allows the circular motion on the rocker arm. The two transportation wheels are connected to the rock arm and can be lowered or raised using the hydraulic cylinder. The wheels used in the design of concept B are similar to the Versatile's offset disk model. Additional to the requirements, the concept can also accommodate roller mounts which can be mounted on the rear end of the mainframe similar to the Field King's disk harrow model. Concept B is more spacious compared to concept A, which allows mounting of instrumentations like, go-pro cameras, laser profilers and dynamometers. The two concepts use similar features from the commercial machines, as discussed in the parameters section. The comparison of features used in concepts and selected commercial machines are shown in Table A3.4 of the appendix section.

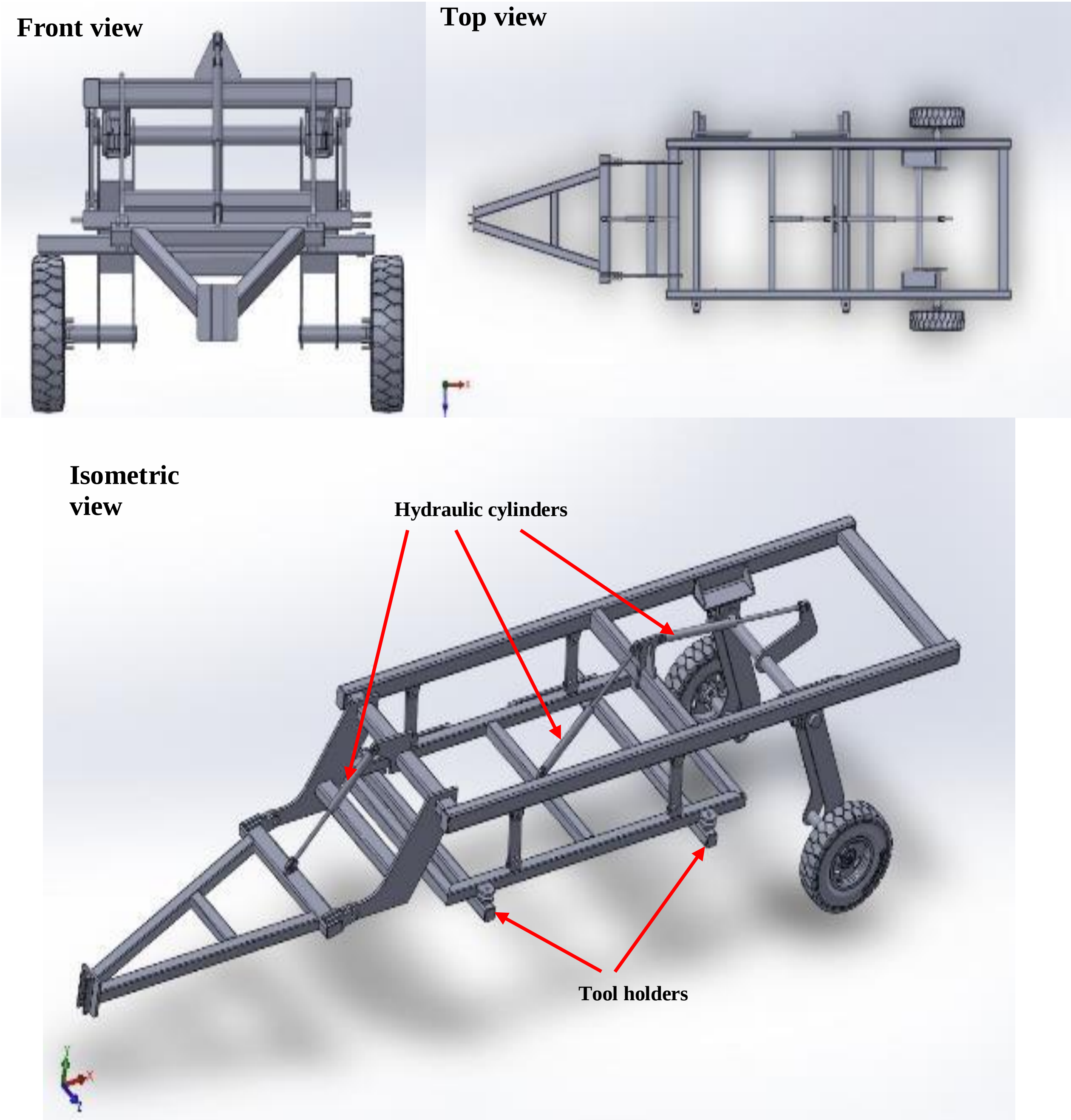


Figure 3.4 Field-testing unit concept B

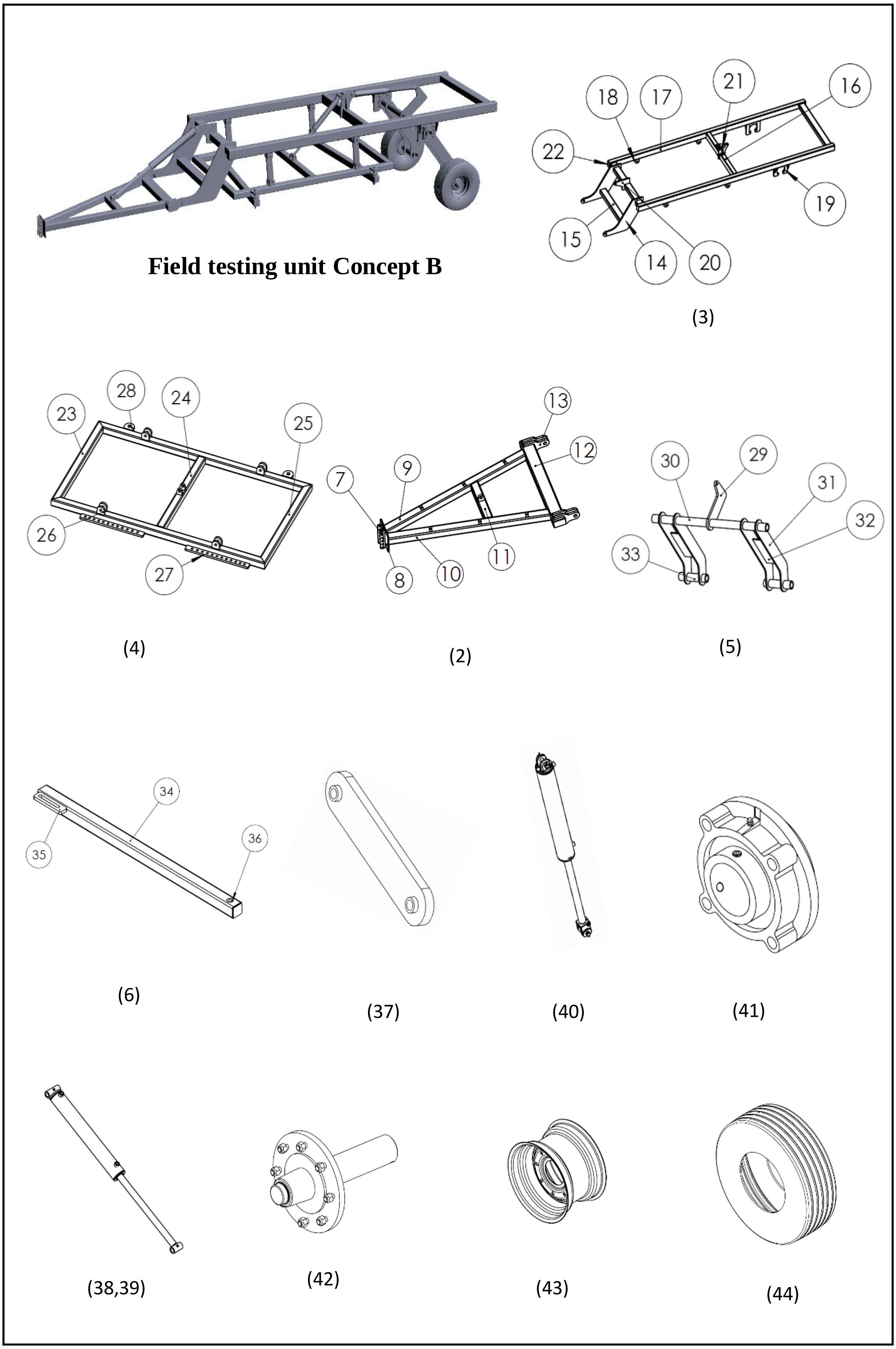


Figure 3.5 Components of the field-testing unit (Concept B)

Table 3.4 List of Components for the field-testing unit (Concept B)

level	No	Part no	Description	QTY	Supplier
Assembly	1	18100	Field testing unit	1	Custom part
Subassembly	2	18010	Hitch frame	1	Custom part
	3	18020	mainframe	1	Custom part
	4	18030	Subframe	1	Custom part
	5	18040	Rock arm	1	Custom part
	6	18050	Toolbar frame	2	Custom part
Hitch frame	7	18011	Hitch mount 6H	1	Pj trailers
	8	18012	Hitch plate ½”	1	Custom part
	9	18013	4/4” frame_1	1	Custom part
	10	18014	4/4” frame_2	1	Custom part
	11	18015	4/4” centre_1	1	Custom part
	12	18016	4/4” main_1	1	Custom part
	13	18017	Pin support_4	4	Custom part
Mainframe	14	18021	Support plate 1”	2	Custom part
	15	18022	4/4” front support	1	Custom part
	16	18023	4/6” center supporting frame	3	Custom part
	17	18024	4/6” side frame	2	Custom part
	18	18025	Subframe pin support	8	Custom part
	19	18026	Hub support plate ½”	2	Custom part
	20	18027	Hyd support_1	1	Custom part
	21	18028	Hyd support_2	1	Custom part
	22	18029	Cover plate	4	Custom part

Table 3.4 list of Components for the field-testing unit (Continued...)

level	No	Part no	Description	QTY	Supplier
Sub frame	23	18031	4/4” frame_1	2	Custom part
	24	18032	4/4” frame_2	1	Custom part
	25	18033	4/4” frame_3	2	Custom part
	26	18034	Subframe_pin support	8	Custom part
	27	18035	1” gang angle plate	2	Custom part
	28	18036	Pivot supports	4	Custom part
Rock arm	29	18041	Back hyd_support	1	Pj trailers
	30	18042	4” tube	1	Custom part
	31	18043	Rockarm_support	4	Custom part
	32	18044	Support plate_22	2	Custom part
	33	18045	3” Wheel hub support	2	Custom part
Toolbar frame	34	18051	4/4” tool frame	2	Custom part
	35	18052	1” Bolt support plate	1	Custom part
	36	18053	1” pivot tube	3	Custom part
Other parts	37	18061	Support link	4	Custom part
	38	18062	Hyd cyl_1 3*20	1	Princes auto
	39	18063	Hyd cyl_2 3*20	1	Princes auto
	40	18064	Hyd cyl_3 4*30	1	Princes auto
	41	18065	Shaft bearing	2	Motion industries
	42	18066	Wheel hub	2	versatile
	43	18067	rim	2	versatile
	44	18068	Fs 24 tyre	2	versatile

3.3.1 Concept selection

The importance of generated concepts and selected commercial machines is rated based on a scale of 1 to 5, with respect to the functional requirements. A different criterion was formed for all the functional requirements, as shown in Table A3.4 of the appendix section. For example, supporting different tools (functional requirement 1) is rated as 1 if the machine supports single type of tool, and it is rated 5 if the machine supports all the selected tools and a rear attachment (e.g. roller basket). Similar rating was provided for all the selected machines and proposed concepts, and they are shown in Table 3.5.

Table 3.5 Summary of importance rates for proposed concepts and selected machines

No.	Functional requirements	Imp	Concept A	Concept B	Machine A	Machine B	Machine C
1	Supporting different tools	5	4	5	3	2	2
2	Traveling at high speeds	3	5	5	3	2	3
3	working in field conditions	5	5	5	5	3	3
4	Travel on highways	4	3	5	3	5	5
5	Safety during transportation	3	5	5	1	5	1
6	Tool perpendicular to the ground	4	5	5	1	5	5
7	Toolbar gang angle flexibility	3	3	4	3	1	3
8	Ballast holders	2	1	1	1	1	1
9	Different working depths	5	4	4	2	3	1
10	Parking stability	3	5	5	1	5	5
11	Hydraulic cylinder operation	4	3	5	5	3	2

Furthermore, the importance rates of the machines are calculated using the following formula:

$$T = \sum_{i}^{n} d_i \, z_{ij} \qquad (3.3)$$

where, T is the total weight factor of the machine with respect to the functional requirement, d_i is the importance of the i_{th} functional requirement, and z_{ij} is the relative rate of the functional requirement for each machine. For example, the importance of functional requirement 1 is 5, and the importance rating corresponding to concept A is 4. Consequently, the total weight factor corresponding to the functional requirement is 5×4=20. As shown in

Table 3.6 Summary of the total score of comparisons

No.	Criteria	Concept A	Concept B	Machine A	Machine B	Machine C
1	Support different tools	20	25	15	10	10
2	Travel at high speeds	15	15	9	6	9
3	work in field conditions	25	25	25	15	15
4	Travel on highways	12	20	12	20	20
5	Safety during transportation	15	15	3	15	13
6	Tool perpendicular to the ground	20	20	4	20	20
7	Gang angle flexibility	9	12	9	3	9
8	Ballast holders	2	2	2	2	2
9	Different working depths	20	20	10	15	5
10	Parking stability	15	15	3	15	15
11	Hydraulic cylinder operation	12	20	20	12	8
Total		165	189	112	133	126
Rank		2	1	5	3	4

In Table 3.6, the conceptual designs with the selected machines are ranked based on their total weight factors. Concept B is ranked first with a score of 189. Therefore, concept B is selected for detail design and analysis to finalize the design dimensions and parts for manufacturing. The next step was to determine the general parameters governing the dimensions and parts of the field-testing unit.

3.4 General parameters

3.4.1 Width of the machine

Several factors were considered to determine the width of the field-testing unit. The width of the machine acts as the major dimension for all the components including, mainframe, subframe and hitch frame. The design requirements and concerns to select the width of the machine are shown in Table A3.5. The first factor is the provincial road rules of Manitoba, which states that the vehicle should have a special permit if the vehicle exceeds the width limit (2.6 meters) to travel on highways. The second factor is that the wheel tracks on the ground after travelling would affect the measurements related to soil disturbance of the soil-engaging tools. Based on the first factor, it was decided that the machine width should be less than 2.6 meters as stated by the law, so that no permit would be required for the machine to travel on highways.

In order to satisfy the second factor, inner distances of commercial tractor tires were studied, and it was found that the distance ranged between 96 - 156-inches as shown in Figure 3.6. This means that the available width for soil related measurements in the field is 96 – 156 in, as those measurements should not be performed on the wheel tracks of tractor. The transportation wheels were decided to be located outside tractor wheel tracks to increase the field measurement area. The selection process for the wheels involve studying different tires used in the commercial machines and are shown in Table A3.6. Good year FS 24

340/60R16.5 radial tires were selected for the field-testing unit. The maximum total width of the unit was set to be 2.4 meters (96 inches), closer to the width limit (2.6 meters) to maximize the space available for soil measurements. In summary, this will also avoid any special transportation permit required to transport the field-testing unit on highways, and at the same time provide a field measurement area as wide as possible.

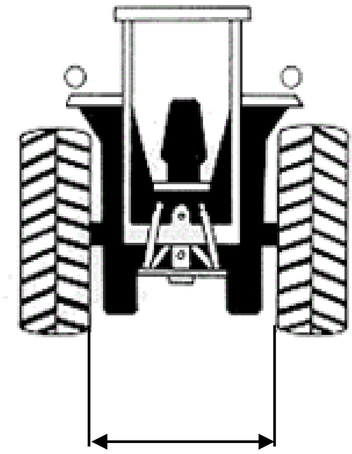


Figure 3.6 Wheel spacing in commercial tractors

3.4.2 Toolbar height and motion range

Different soil engaging tools are to be attached to the toolbar of the machine. It is essential to determine the toolbar height and motion range needed to support different tools and to set them at different working depths. The parameters selected also play an important role in further determining the specifications required for frame, support linkages, and other components.

There are various soil-engaging tools used for tillage and seeding. Tillage tools include disc, coulter, sweep, chisel, and subsoiler. Seeding tools include C-shank openers, hoe openers, and cross-slot openers. Vertical tillage tools are the main types of tools to be tested using the testing unit. Different tools have different shank sizes and working depths. These parameters determine the toolbar height to the ground and the required motion range of the toolbar. Also, different tools have different soil cutting forces that are external loads acting on the structure of the frame. Therefore, the strength of the structure is also affected by the type of tools mounted on the field-testing unit.

Tools selected for the field-testing unit and their dimensions are listed in Table 3.7. Dimensions of tools like heights, lengths, minimum working depths, and maximum working depths were obtained from commercially available tools, to determine working parameters of selected tools. The mount type of the tools was found to be same in selected tools. The mounting is done by bolting the tool to a 4x4-inches cross-section of the toolbar.

Table 3.7 Summary of tool dimensions and working parameters (inches)

Type of tool	VT disk	Subsoiler	Opener	Sweep cultivator
Total height (H)	33	34	30	16
Total length (L)	30	26	20	18
Min working depth (d_{min})	2	2	2	2
Max working depth (d_{max})	8	16	3	4
Min toolbar height (h_{min})	25	18	27	12
Max toolbar height (h_{max})	43	44	40	26

The residue cover in the field varies from 5 to 10 inches. The clearance from the lowest point of the tool to the ground was considered as 10-inches (constant) to avoid any residue clogging of tools during the field transportation. The maximum and minimum heights of the tool during transportation and field operation are shown in Figure 3.7. The transportation height, i.e. the maximum height of the toolbar, is the sum of the tool height and the toolbar clearance to the ground. The maximum height of the toolbar was calculated using the following formula:

$$H_{max} = h + c \qquad (3.4)$$

Where H_{max} is the maximum toolbar height from the ground, h is the total height of the tool (Table 3.7), c is the clearance from the lowest point of toolbar to the ground (C = 10 inches).

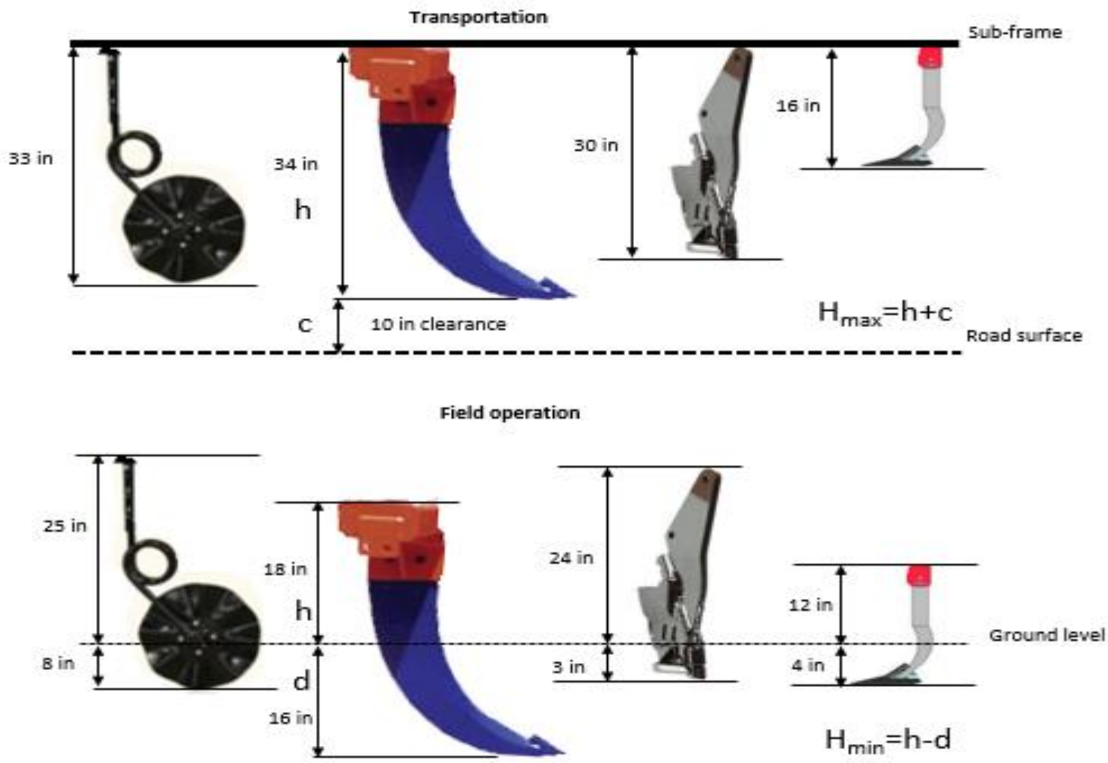


Figure 3.7 Maximum and minimum heights of the tool during transportation and field operation.

To determine the maximum toolbar height, the value of h is selected from the height of the subsoiler tool (34 inches), as it has the maximum height among the four tools. Thus, during the transportation, the maximum height of the toolbar should be 44 inches (34+10) from the ground. The operation height in field testing, i.e. the minimum height of the toolbar, is the toolbar height when the tool is engaged with soil. Similarly, the minimum height of the toolbar can be calculated using the following formula:

$$H_{min} = h - d_{max} \qquad (3.5)$$

where H_{min} is the minimum toolbar height from the ground, h is the total height of the tool (Table 3.7), d_{max} is the maximum working depth of the tool (Table 3.7). To determine the minimum toolbar height, values of H and d_{max} are taken from the sweep cultivator that has the minimum height of all tools. The lowest toolbar height is 12 inches (16 minus 4) when the sweep cultivator is working at the maximum depth of 4 inch.

Given the maximum and minimum heights of the toolbar, vertical motion range of the toolbar can be calculated using the following equation:

$$\Delta H = h_{max} - h_{min} \tag{3.6}$$

Thus ΔH = 32 inch. Adding 8 inch for additional space helps in mounting and dismounting the tools, a 40-inch motion range is required to operate the selected tools in the field. The linkages and rock arm were designed based on the required motion range.

3.4.3 Toolbar angle

Tillage tools sometimes are fixed in an angle to mix the residue with the soil more or to loosen more soil. The toolbar angle (angle between toolbar and subframe, also named as gang angle as mentioned above) in commercial machines varies from 0 to 22 degrees. The toolbar angle is adjusted using different mechanisms in commercial machines. The most common type of mechanism used by selected commercial tillage equipment is bolted pivots and hydraulic systems. The toolbar angle in the field-testing unit is only adjusted in the beginning of the tests, unlike commercial machines where the angle can also be changed during field operations. Hence, to make the mechanism as simple as possible, pivoted bolts are used in the field testing-unit.

Two individual toolbars are mounted on the subframe of the field-testing unit. The proposed mechanism used in this concept is similar to the Versatile's offset disk model. Each toolbar measures 58 inches, and multiple tools can be directly attached to the toolbar. The toolbars are pivoted on one side and bolted on the other side, as shown in Figure 3.4. The toolbar has multiple holes to adjust the angle from 0 to 22 degrees. The detailed calculation for hole placement to achieve the angle is shown in Figure A3.1 and table A3.7.

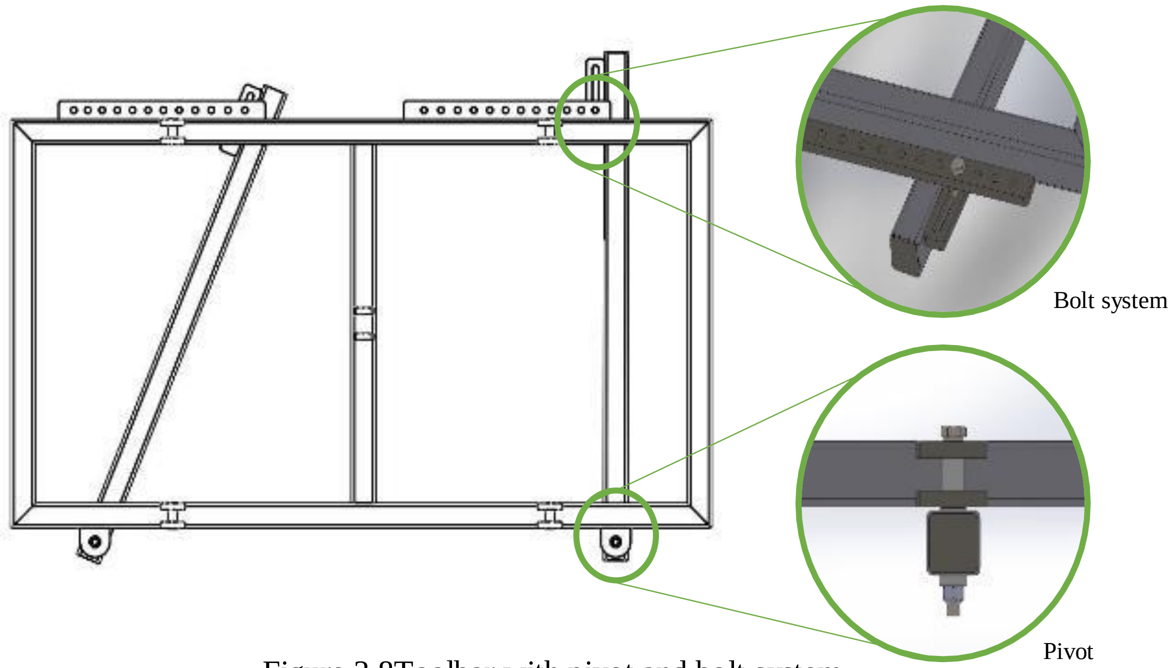


Figure 3.8Toolbar with pivot and bolt system

3.4.4 Hydraulics / Driving power

The tillage machines selected for comparison use hydraulic systems to power different operations like controlling depth, folding-unfolding of arms, and maintaining height of the machine. Hydraulic cylinders are also used as the driving power for the field-testing unit based on two factors. The first factor is that the extensive use of hydraulic actuators in the field of agricultural machinery guaranteed the functioning of the machine. The second factor is that tractors are already built with hydraulic couplers, making it the best possible driving force for the field-testing unit. The hydraulic couplers provided on the tractor determine the number of hydraulic cylinders that can be used. Generally, farm tractors consist of two to six hydraulic couplers. Three hydraulic cylinders are used in the design. The first cylinder is attached to the hitch frame and mainframe to control the height of the hitch. The second cylinder is connected between mainframe and subframe to control the operating depth of the subframe, and the third cylinder is connected to the mainframe and rocker arm to control the height of the mainframe. The selection criteria for the hydraulic cylinders and the selected hydraulic cylinders are discussed in Appendix 3.

3.4.5 Safety lights

The field-testing unit will be travelling on highways and field conditions. Safety lights are required in a trailer type vehicle by law when travelling on highways. Different safety lights and their features were studied to determine the best possible solution. The safety lights for the vehicle operate on a battery or a 12v power supply. The criteria and evaluation of the selected lights are listed in A3.11. The field-testing unit does not have its own power source as it is a trailer type vehicle. A 12v power output is provided in trucks and tractors with a towing coupler. The 12v magnetic tow lights are selected for the field-testing unit. The lights consist of a magnetic base which can be easily detached from the machine during field testing.

3.5 Assembly of the field-testing unit

The assembly of the field-testing unit is divided into subassemblies and components as discussed earlier in the concept B. The final length, width, and height of the unit after assembly are 314-inches (7.97 meters), 82-inches (2.08 meters) and 63-inches (1.6 meters), respectively, as shown in Figure 3.9. The motion range of the testing-unit is 40 inches (20 inches from the subframe cylinder and 20 inches from the rocker arm cylinder). The assembly consists of total 188 parts including fittings and fasteners. The five subassemblies of the field-testing unit are hitch frame, mainframe, sub-frame, toolbar, and rocker-arm. The main assembly of the unit is divided into three clusters. The first cluster consists of the A (hitch frame), the second cluster consist of B, C, and D (mainframe, sub-frame, and toolbar), and the third cluster consist of E (rocker-arm) as shown in Figure 3.10.

The hitch frame of the field-testing unit measures 85-inches. A 4×4 frame is used for manufacturing the custom hitch. The height required for the hitch is determined using the drawbar height from tractors which vary from 15 to 19 inches (HOSTA, connecting implements to the tractor) and 17 inches for truck hitches. The hitch of the unit can be adjusted from 15 to 19 inches to provide hitching for tractors and trucks. Commercially available trailer hitch is used in the design for convenient attachability of the unit.

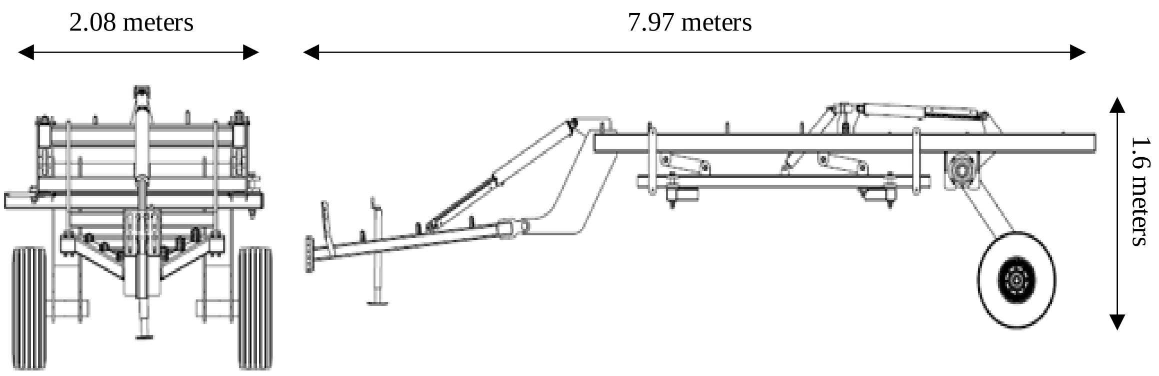


Figure 3.9 Length, width, and height of the Field-testing unit

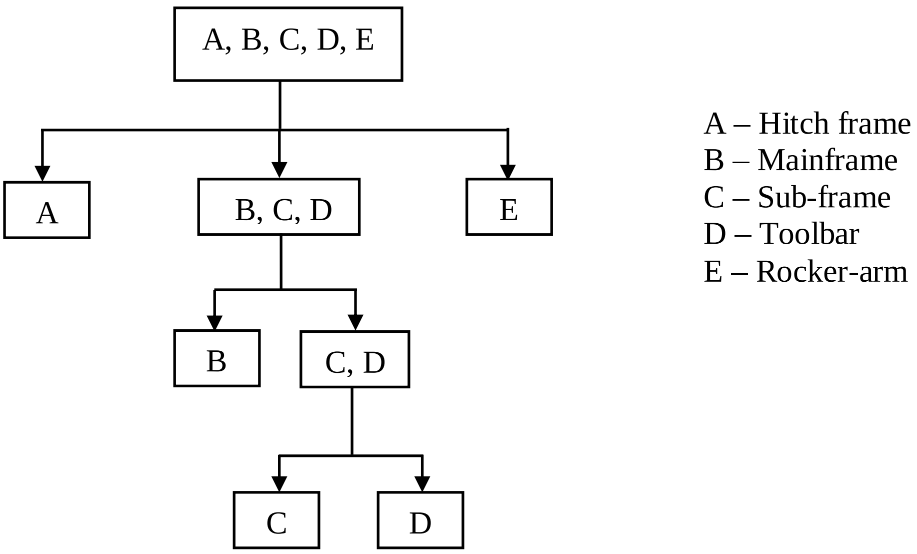


Figure 3.10 Clustering of the subassemblies for the field-testing unit

Mainframe is the main part of the field-testing unit, which houses most of the subassemblies and parts. Hitch frame, subframe frame, and rocker-arm are connected to the mainframe. The mainframe measures 238-inches in length and holds all the three hydraulic cylinders of the field-testing unit. Mainframe, sub-frame, and toolbar are directly connected to each other and considered as a single cluster. Further, the toolbar and sub-frame are considered as a cluster since they are directly connected to each other. The last cluster is the rocker arm subassembly connected to the mainframe by hydraulic cylinder and Plummer block. The rocker arm subassembly consists of two transportation wheels attached to the frame.

In the next chapter, the CAD model of the designed field-testing unit is imported to Ansys for structural analysis. The forces acting on the frames, input parameters, constrains, and results of the structural analysis are discussed.

Chapter 4 Structural analysis

4.1 Introduction

The structural analysis of field-testing unit was conducted to verify the structural integrity of the entire machine structure, including the mainframe, subframe, toolbars, rock arm and fasteners used in the machine. The purpose of this chapter is to verify that the current structural configuration withstanding the calculated worst-case force scenarios. Structural analysis was performed on the assembly of the field-testing unit for two cases. Case 1 is with draft forces from subsoiler, and Case 2 is with draft forces from VT (Vertical Tillage) disk.

The analysis was performed using ANSYS structural 18.2 solver. Finite element analysis (FEA) was used to determine the maximum stresses, deformations, and factor of safety for the considered materials. The solver can determine the resulting stress and deformation of the body at a point in a direction or across the body. A similar analysis was performed (Hosseinpour, 2013) to verify the structural strength of the wheelchair component. This type of study is used for solving simple statics problems on complicated geometries. Upon analysis, we can determine failure points on components and factors of safety at those points. The results obtained from the analysis can be used to improve the design by using better supports and fasteners at the point of failure.

4.2 Forces acting on the field-testing unit

4.2.1. Forces from soil-engaging tools

Soil cutting forces of the soil-engaging tools are design loads of the field-testing unit. These forces include forces in three directions, horizontal, vertical, and lateral forces. The horizontal force is also known as the draft force. Draft force is the soil resistance to the tool. Thus, its direction is opposite to the direction of travel. This force is the most critical force among all the forces, as it determines the power requirement of the tractor. Force can be multidirectional, depending on the type of soil-engaging tools. Shank-type tools such as subsoilers and cultivators, typically have downward vertical forces, which helps to maintain the working depth. Disc-type tools, such as rotary vertical tillage tools, typically have upward vertical forces to pull the tools out of the soil. The lateral force is applicable only to tools with an asymmetric geometry, such as concave discs and side-band openers. Vertical and lateral forces are lesser in magnitude compared to horizontal forces. Hence in this study, they were assumed to be negligible, and only draft force was used to calculate forces exerting on the toolbar frame. Figure 4.1 shows the draft forces (Pc), weight (W) and reaction (R) acting on a typical agricultural tool.

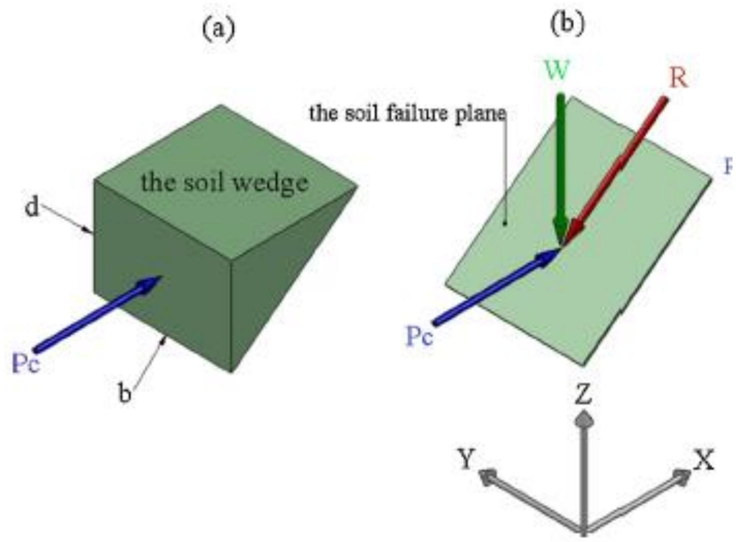


Figure 4.1 Typical draft force (Pc), weight (W) and reaction (R) acting on a typical agricultural tool. on the tool (Onwualu et al. 1993)

The analysis approach of the machine was started with calculating draft force for the considered tools. Draft force can also be defined as the force required to pull an agricultural implement. Standards from ASABE (American Society for Agricultural and Biological Engineers) were considered for the calculation of draft force of the tools. Table A4. 1, in the appendix section, shows the standard machine parameters and soil parameters to be considered for the draft force calculation of the tool. Variables for calculating the draft force vary for different types of tools. For example, the draft force for subsoiler tool is calculated for a single tool. Whereas the draft force is applied for the opener, VT disk and plough are calculated for the width of the tool assembly in the ASABE standard calculations. For the tillage tools operating at low depths, the draft also depends on the soil texture, depth, and geometry of tools. The typical draft force exerted on a tool can be calculated using Formula (4.1):

$$D = F_I[A + B(S) + C(S)^2]WT \qquad (4.1)$$

where,

D = implement draft, N (lbf),

F = dimensionless soil texture adjustment parameter (Table A4.1 appendix),

I = 1 for fine, 2 for medium and 3 for coarse-textured soils,

A, B, and C are machine-specific parameters (Table A4.1 appendix),

S is operating speed, km/h (mile/h),

W is machine width, m (ft) or number of rows or tools (Table A4.1 appendix),

T is tillage depth, cm (in.) for major tools and 1(dimensionless) for minor tillage and seeding tools.

The working parameters which gave maximum draft forces were considered, and the draft force was calculated for subsoiler, seed opener, sweep, and VT disk to simulate the worst-case scenarios. Table 4.1 shows the calculated draft force values for the selected tools. These forces were used to calculate the load acting on the toolbar frames and respective loads on the other frames of the field-testing unit for two cases. The first case is with attached individual tools, and the second case is with the assembly of tools.

Table 4.1 Calculated draft forces for selected tools

Type of tool	Draft force (kN)	
Subsoiler	10.2	Single tool
Sweep plough	10.9	Tool assembly
VT Disk	13.3	Tool assembly
Seed opener	3.8	Tool assembly

As shown in Table 4.1, Subsoiler shows the highest draft force per tool for the considered parameters (A4.2) at 10.2 kN, and VT disk has the highest force for the width of tools at 13.3kN. Draft forces from subsoiler and VT disk were used to study stresses on the field-testing unit. Parameters used in calculating the draft force are shown in Table A4. 1 and A4. 2 of the appendix sections.

4.2.2. Frictional force of the wheels

The force that resists the motion of a body rolling on a surface is called the rolling resistance or rolling friction. The wheel rolling resistance generated during the field operation by the field-testing unit was calculated using the formula:

$$F_r = c\,W \qquad (4.2)$$

$$W = m\,a_g \qquad (4.3)$$

where,

F_r = rolling resistance or rolling friction,

c = rolling resistance coefficient (appendix A4. 3),

m = mass of the body (kg),

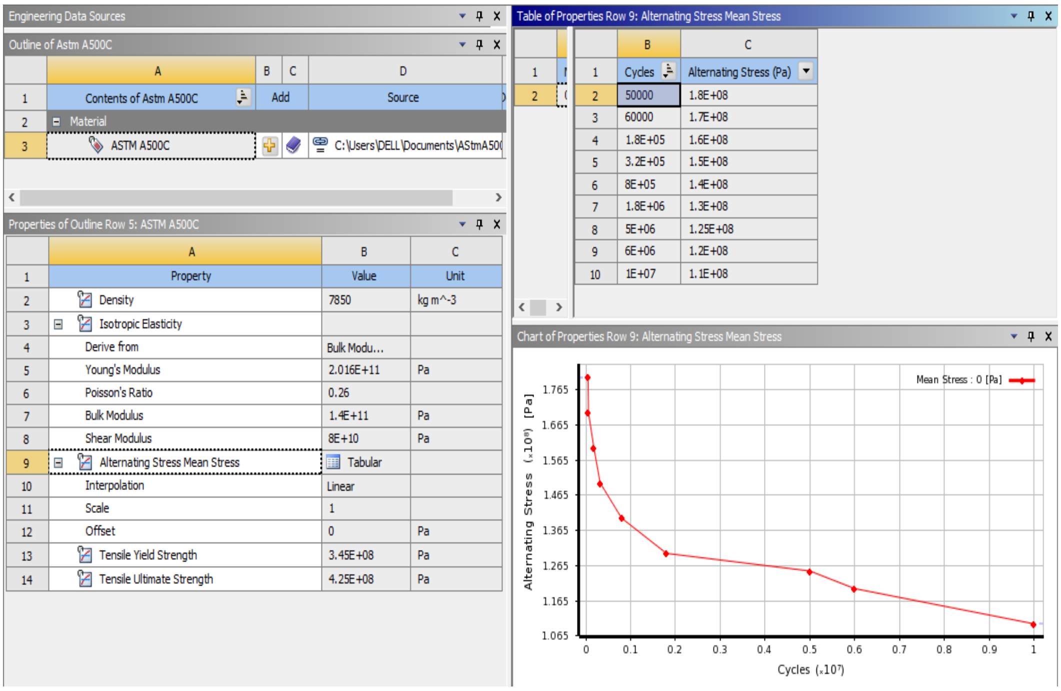
a_g = acceleration due to gravity (9.81m/s^2).

The mass of the field-testing unit was 1487 kg, as shown in Figure 4.3 in the material properties section. The rolling resistance at the two wheels of the testing unit was found to be 583.49 N.

4.3 Material properties

The field-testing unit is built from two types of ASTM A 500 beams differentiated by their cross-sections. This type of material is extensively used as structural members in agricultural machines, bridges, buildings or general structures. The alloy can be easily welded, bolted or riveted for structural applications. The 4x6-inch frames are used for the mainframe, and 4x4-inch frames are used for the design of subframes. The weld plates and support plates used in the design are also made of ASTM A 500 material. Fasteners used in the field-testing unit like bolts, nuts, pins, and other child parts are grade 5 steel material. Figure 4.2 shows the mechanical properties of the selected materials. The ASTM A 500 beams have yield strength of 345 MPa and ultimate strength of 425 MPa with the density of 7850 kg/m^3. The grade 5 steel was initially selected as the material for fasteners. The material has a yield strength of 634 MPa and an ultimate strength of 827 MPa with a density of 7800 kg/m^3. As this type of material is already being used for manufacturing commercial agricultural machines, the field-testing unit is expected to meet design and application requirements.

a)



b)

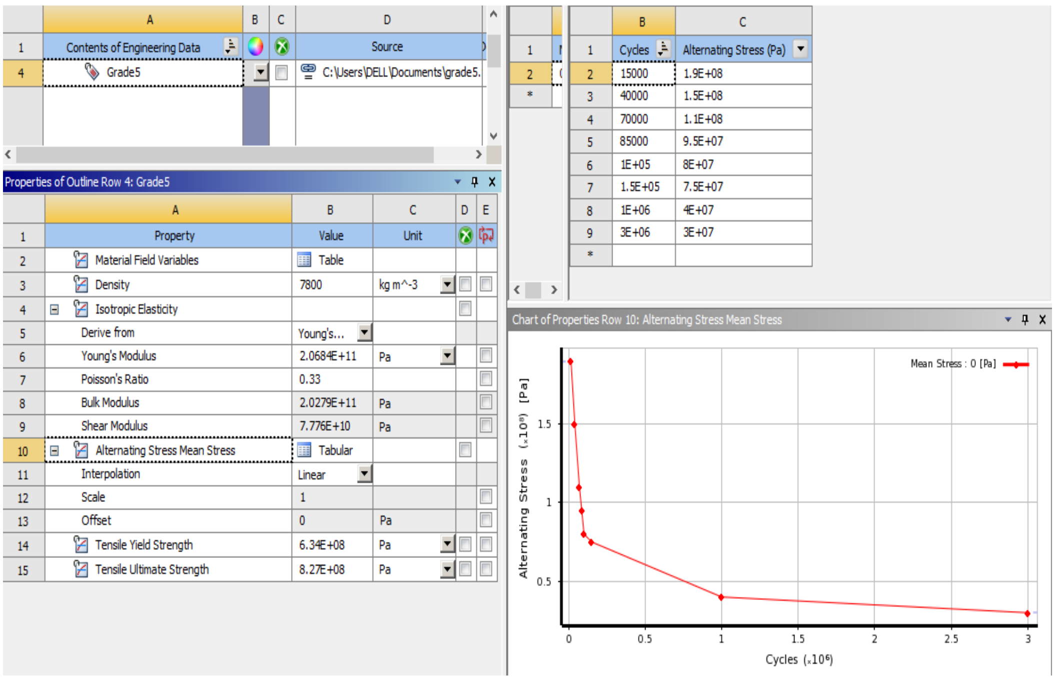


Figure 4.2 a) Mechanical properties of ASTM A500C in Ansys, b) Mechanical properties of grade 5 steel

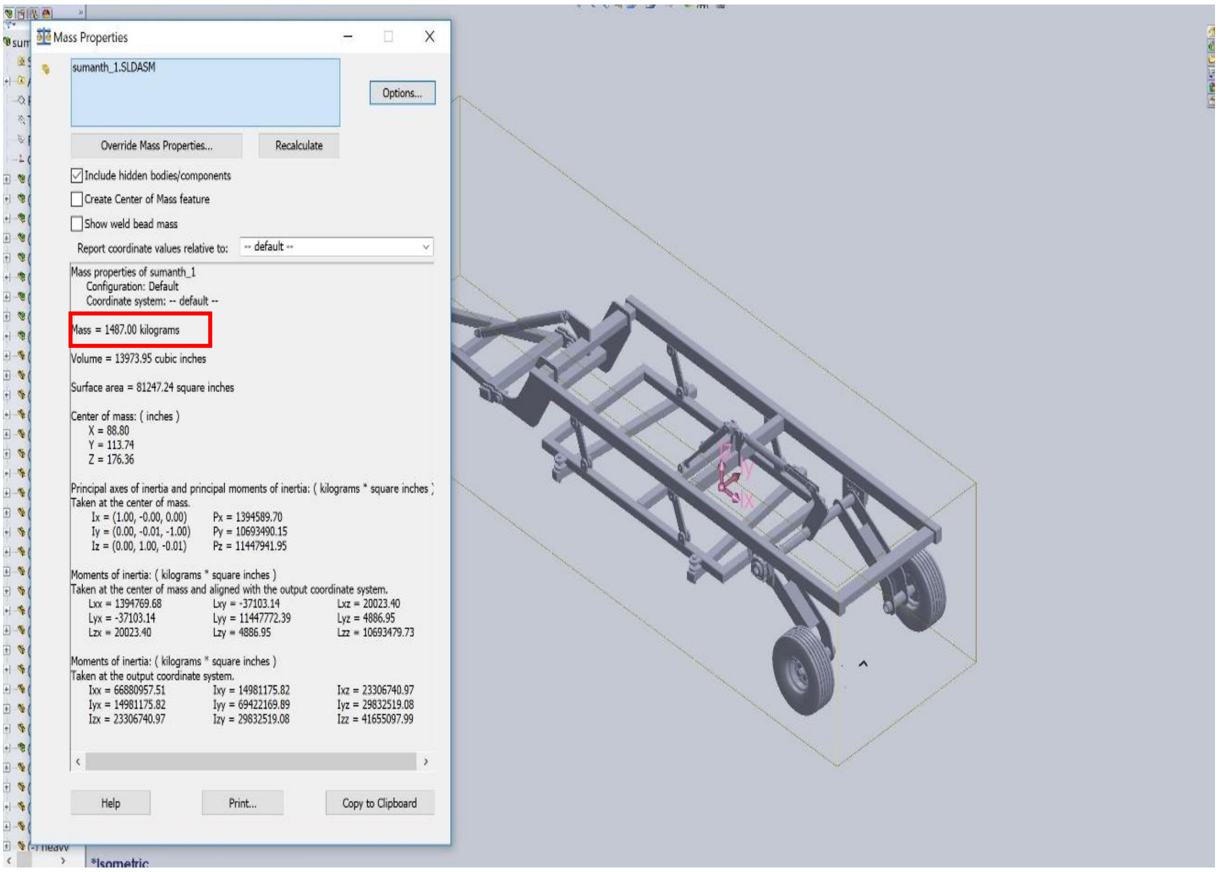


Figure 4.3 Mass of the field-testing unit and center of gravity

4.4 Geometry and meshing

The right-handed Cartesian coordinate system was used to define the geometry in the software. When referring to specific beams, the orientation is viewed looking in the direction of the positive x-axis, as shown in Figure 4.4. The hitch is dictated by the negative x-axis while left and right dictate positive and negative z-axis directions. Components below the mainframe represent bottom beams in the negative y-axis.

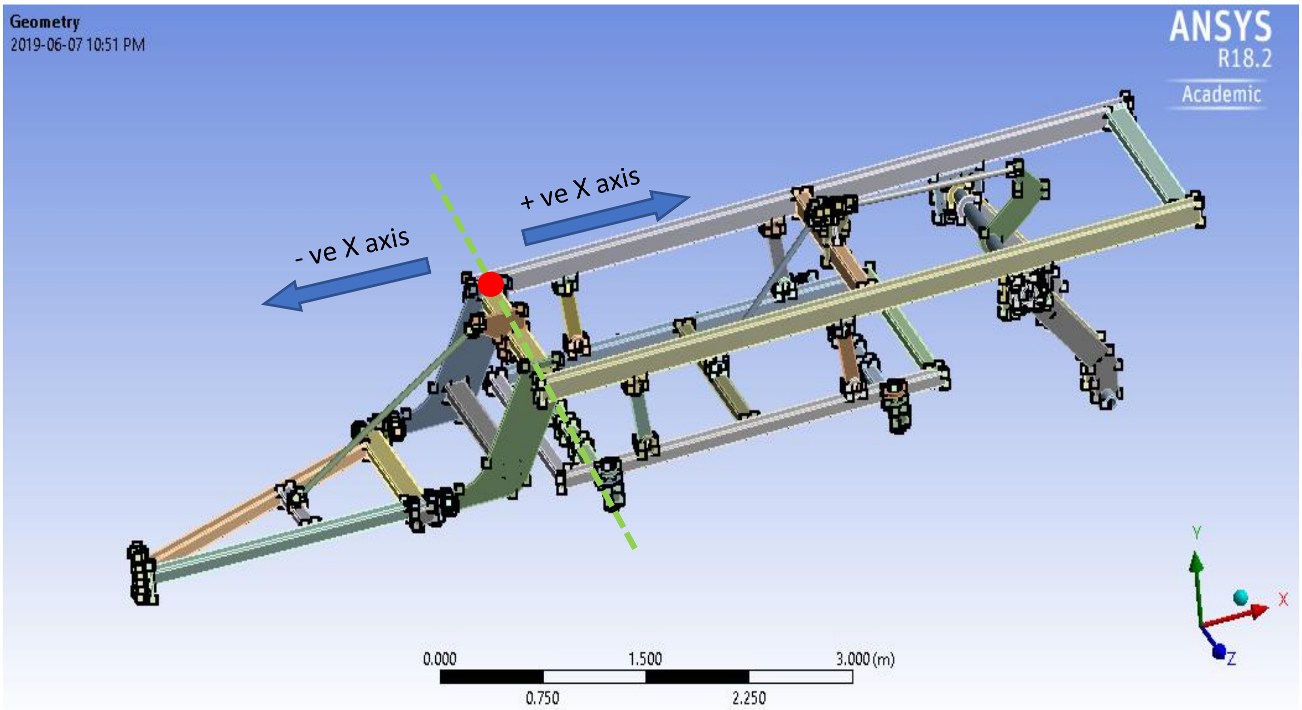


Figure 4.4 Right-handed cartesian coordinate system showing positive and negative X-axis with the origin of coordinate system marked with a red dot.

The geometry of the model is divided into a total of 494071 nodes and 149721 mesh elements, as shown in Figure 4.5. While generating the mesh, it was taken care to provide as much hexahedron elements as possible, while for curved surfaces, mixed mesh was assigned. These elements lead to higher degree polynomial equations, hence more accurate real-time results will be obtained. The target quality was set to 0.05 with higher smoothing ratio, and the minimum edge length was set to 6.57×10^{-4} m. Also, the transition between two different structural components was made smooth to minimize the numerical approximation across the transition. To perform the grid-independent study, even finer mesh was used to compare the results. The compared mesh had 568937 nodes and 172457 mesh elements. It was found that the factor of safety (FoS-15) for both cases was similar; hence, for saving the computational time the mesh with 494071 nodes was selected.

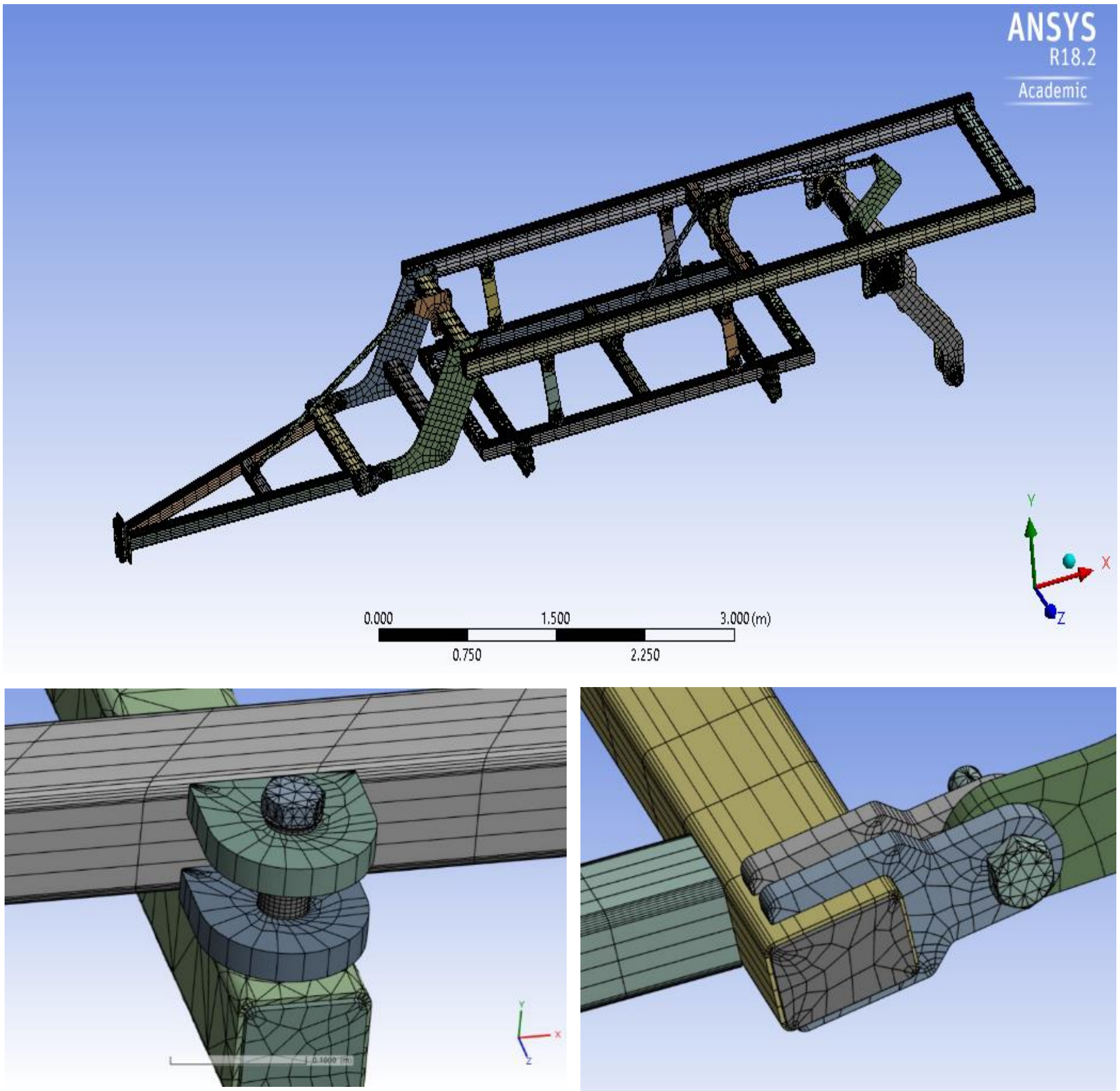


Figure 4.5 Meshing of the field-testing unit in Ansys R18.2

4.5 Constraints

The constraints to components of the field-testing unit were assigned according to field working conditions. The field-testing unit is mounted to the tractor using the hitch. Hence, the hitch is considered as a fixed support and constrained in Y and Z directions. The wheel hubs of the field-testing unit were also considered as fixed supports as the wheel will be in contact with the ground. Three hydraulic cylinders A, B, and C are fixed in their respective working conditions as they will not be operated during field tests as shown in Figure 4.6. Pin, fixed, bolted, and hinged supports were assigned to the field-testing unit. Details of the constraints for individual parts are shown in Table A4. 4 of the appendix section.

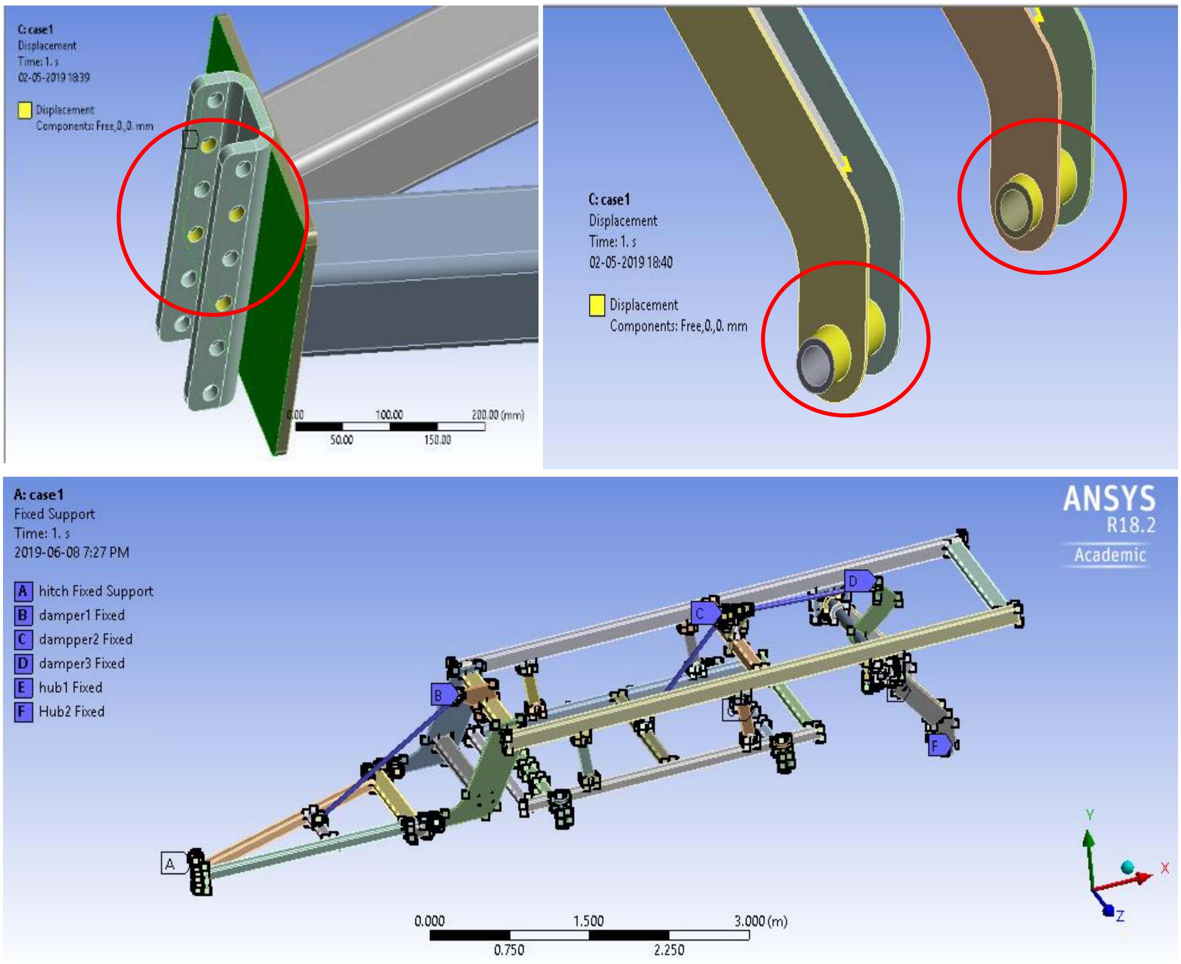


Figure 4.6 Constraints assigned to the model in

4.5.1 Forces and moments

Forces obtained from draft force calculations were applied to the toolbar of the field-testing unit. The setup consists of a single subsoiler attached to the first toolbar and two subsoilers attached to the second toolbar. This setup was designed considering the space available for mounting the tools (60 inches). The optimal spacing of subsoilers was mentioned as 20 inches by Weill (2015). Based on this factor only three subsoilers can be attached to the toolbars of the testing unit in combination (1 in the first toolbar and 2 in the second tool bar or vice versa). There are 3 moments and 5 loads acting on structural parts of the field-testing unit. The forces applied to the field-testing unit in Ansys are shown in Figure 4.7 and moments are shown in Figure 4.8. The tool forces were transferred to the toolbar from tooltip, which also induces a moment on the toolbar. Calculations for moments are due to the shifting of forces from the tool to toolbar, as shown in A4. 6 of the Appendix section. Two case studies were performed to analyze the maximum stress on the field-testing unit. Table 4.2 shows tools and parameters used in both cases. Three subsoiling tools with a space of 18 inches were considered for case one and toolbar width of 56 inches was considered for case 2.

Table 4.2 Parameters used during analysis of field-testing unit

	Tool type	Spacing (inch)	Draft force (kN)	Moment (kN-m)	Friction force (kN)
Case 1	Subsoiler	18	10.2	8.8	1.16
Case 2	VT disk	56(width)	13.3	11	1.16

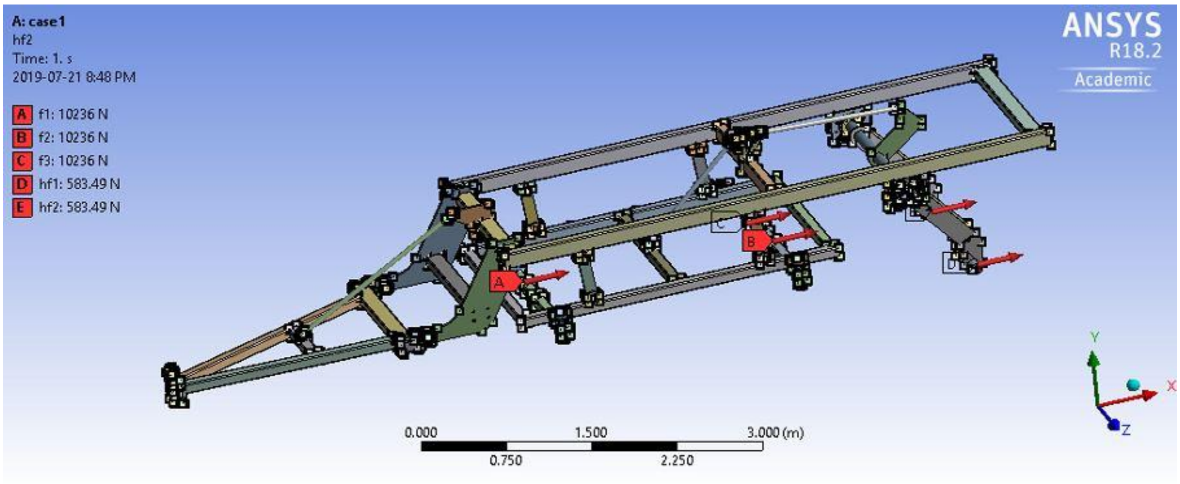


Figure 4.7 Forces applied to the field-testing unit

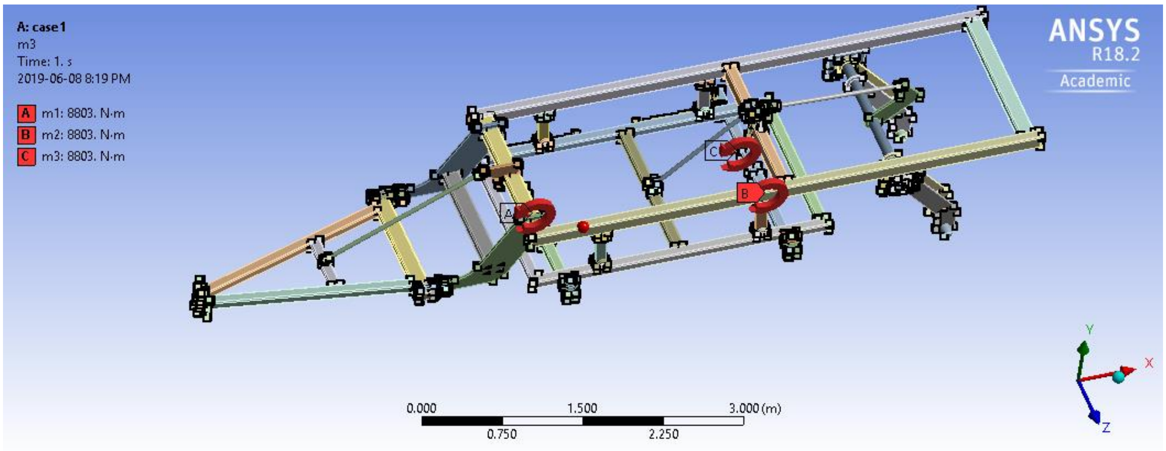


Figure 4.8 Moments applied to the field-testing unit

4.6 Analysis results

Results from the von-mises stress analysis for Case 1 is shown in Figure 4.9. The maximum stress in the geometry was found to be 279 MPa, which is lower than the yield strength of the selected material. It was found that the second toolbar has the maximum stress, as shown in Figure 4.10. It was also observed that toolbar 1 and gang side fastener have a higher range of stress (200-240MPa).

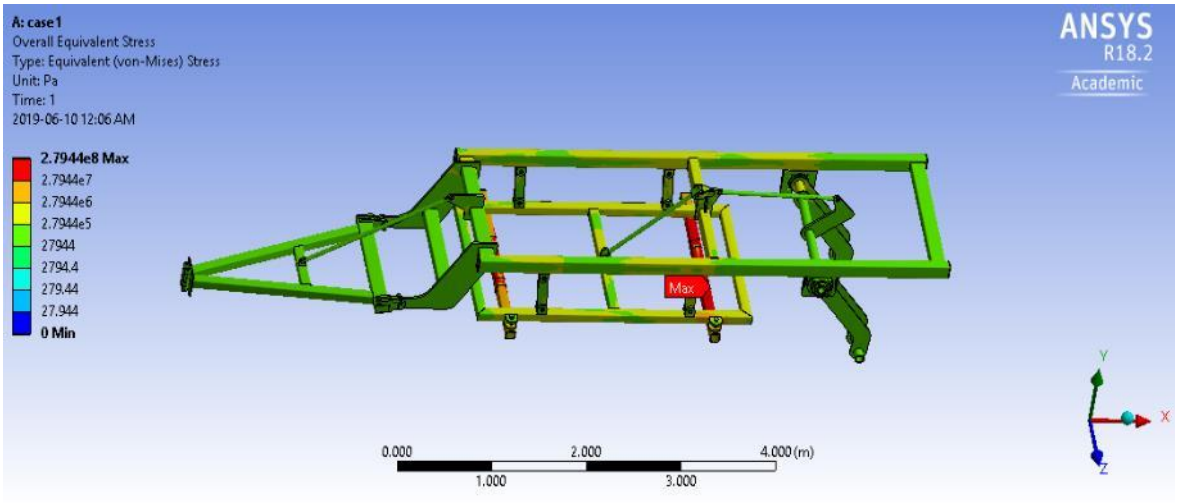


Figure 4.9 Von-mises stress analysis results of the field-testing unit under Case 1 loading condition

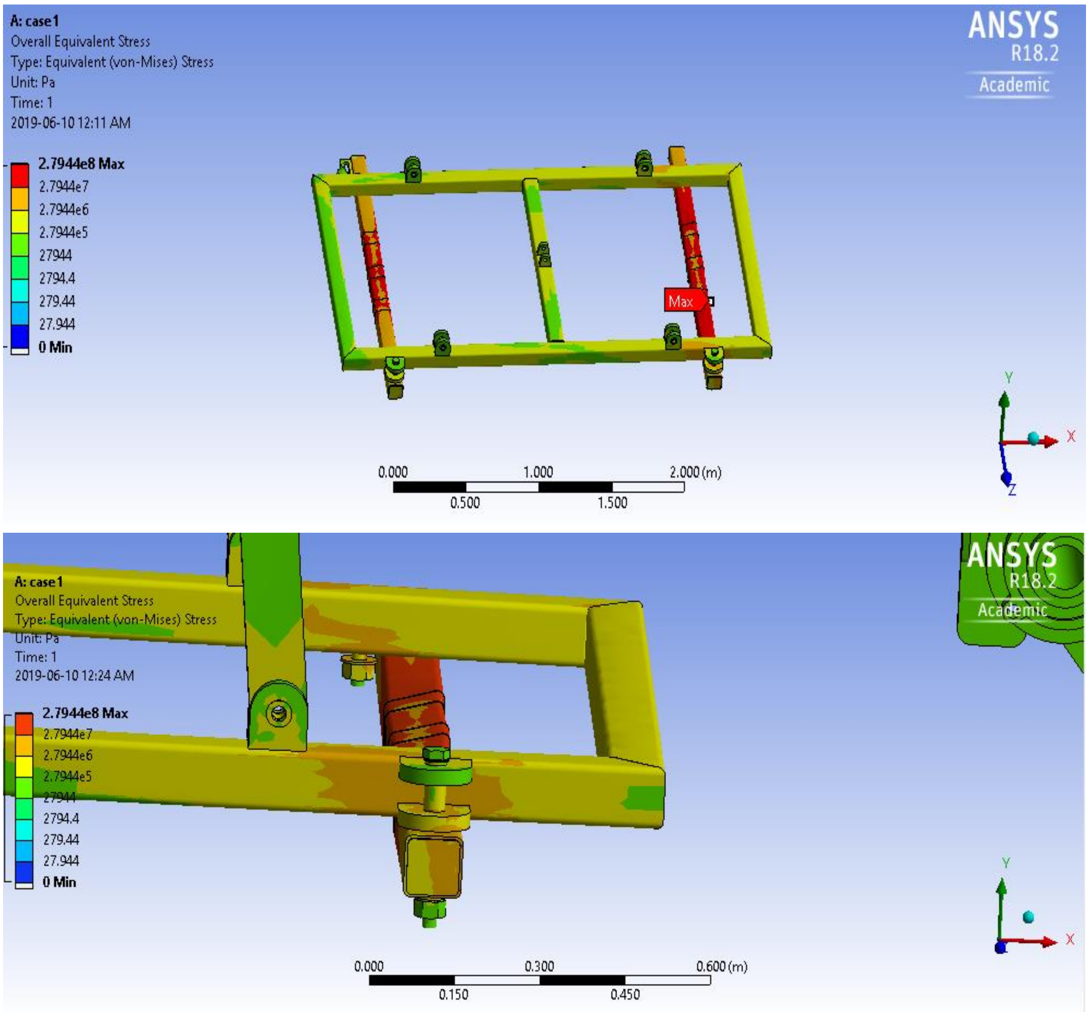


Figure 4.10 Maximum stress observed in the second toolbar of the subframe under Case 1 loading condition

The overall factor of safety for the second toolbar was found to be 1.23. Even though the factor of safety for the toolbars are on the lower side, forces applied to the model were

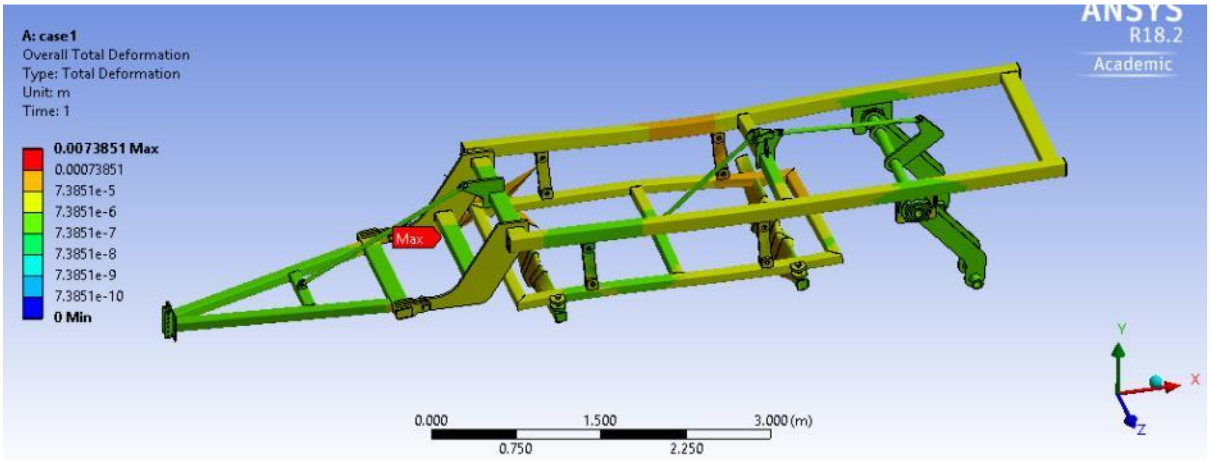


Figure 4.11 Overall deformation on field testing-unit under Case 1 loading and constraint conditions.

calculated for the extreme case scenarios. For example, the maximum speed and operating depth were considered for the subsoiler tool. Details of the compatible tools and changes need to be made to the field-testing unit are discussed in Chapter 5. The deformation caused due to the design loads was also analyzed for the field-testing unit. Figure 4.12 shows the overall deformation of the field-testing unit under maximum load conditions. Figure 4.13 shows the maximum deformation of 0.0073 meters on the gang side mounting plate.

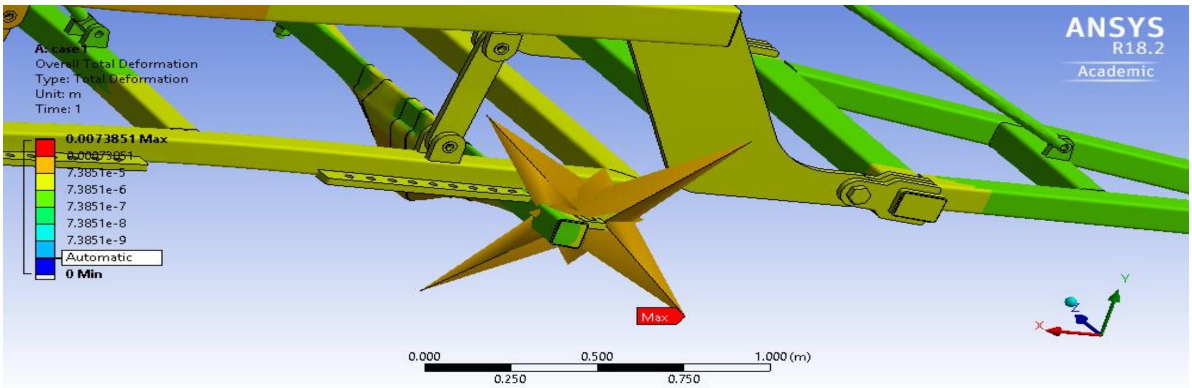


Figure 4.12 Maximum deformation of 0.0073 meters observed in the mounting plate

The deformation caused due to loading conditions may result in inappropriate functionality and affect other components or overall mechanism. To avoid any further damage to the field testing-unit, additional gusset supports were provided to the part, the sheet thickness of the part was increased to eliminate the failure of the part. Upon providing the additional gussets and increasing the thickness of the mounting plate, as shown in Figure A4. 7 of appendix. The gang angle plate was safe for the given design loads. A minimum factor of safety of 2.162 and a maximum factor of 15 were observed in the structural components of the field testing-unit for Case 1, as shown in Figure 4.13.

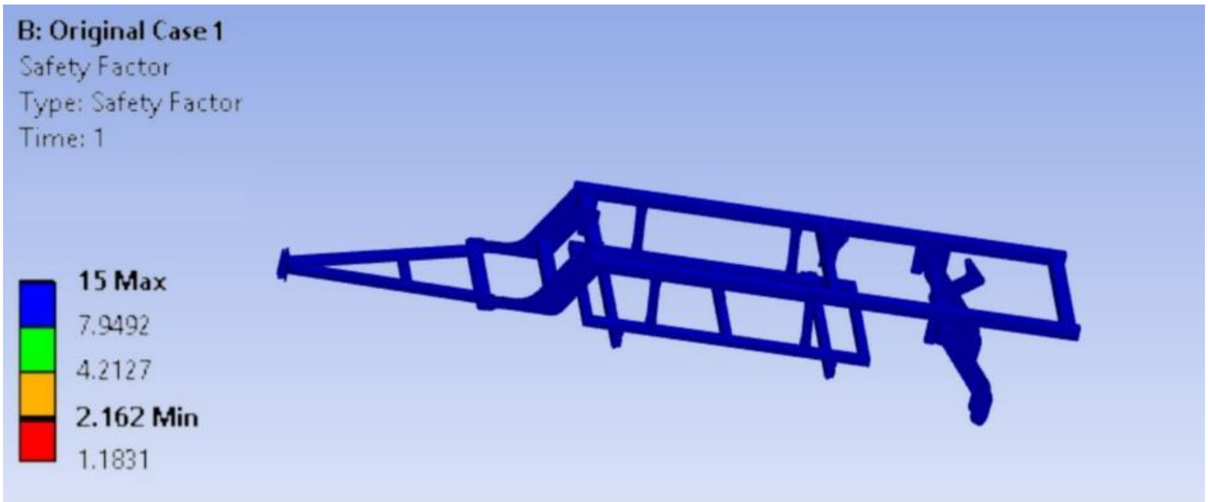


Figure 4.13 Factor of safety for the structural components of the field-testing unit

Case 2 was analyzed by applying a uniformly distributed load of 13.3 KN on toolbars one and two. Primarily, it was observed that the maximum stress of 159.6 MPa occurred on toolbar two. Secondly, toolbar one and gang side fasteners were also observed in a higher range of stress (90-120MPa). Case 2 has considerably less stress compared to Case 1. No failure of parts was observed, and the deformation was negligible. Figure 4.14 shows the equivalent stress developed in the field-testing unit. Detailed images for stress and deformation can be found in A4. 4 of the appendix section.

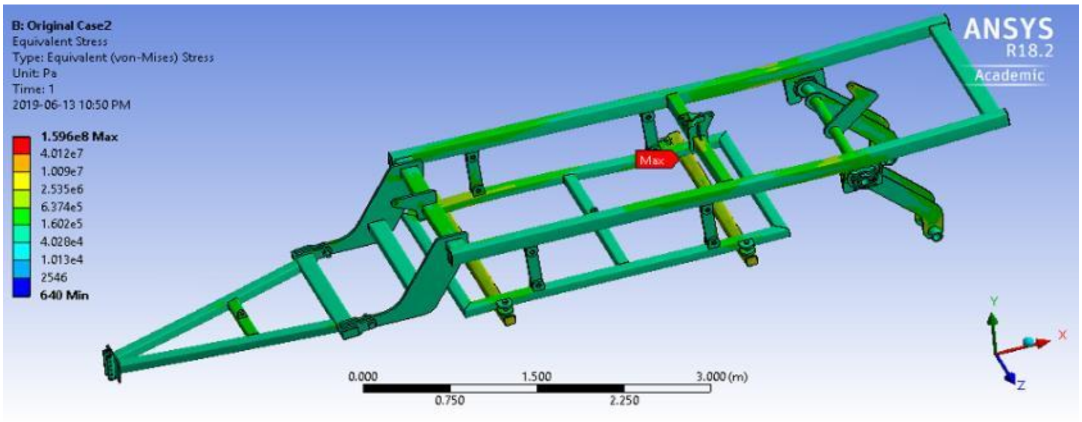


Figure 4.14 Equivalent stress for Case 2 in the field-testing unit

4.7 Machine efficiency and engine power

Theoretical field capacity (TFC) was calculated to determine the efficiency of the field-testing unit during field operations. TFC can be defined as the amount of work performed by an agricultural machinery at a given speed and width of the machine (Smith et al., 1994). The unit of TFC is acres per hour. Equation 4.4 represents the TFC as the product of the width [ft] and speed [mph] of the machine divided by a constant 8.25, which is introduced to convert the multiplication of feet and miles to the area in acres.

$$TFC = \frac{width\ [ft] \times speed\ [mph]}{8.25} \quad (4.4)$$

The calculated TFC (considering the machine is traveling with a speed of 9.3 [mph], and the width of the machine is 5.8 [ft]) is 53.94 acres per hour. The calculated TFC can be used to plan the field tests to determine the time required to operate the machine in the pre-determined testing area.

4.7.1 Engine power

The engine power required to pull and efficiently operate the field-testing unit can be calculated using Equation 4.5.

$$P = F_T V / \eta \quad (4.5)$$

Where,

P = engine power [W],

F_T = total force (sum of rolling resistance force + draft force) acting on the field-testing unit [N],

V = velocity of the tractor [m/s],

η = overall efficiency of the transmission,

$$F_T = F_r + F_d \tag{4.6}$$

$$F_r = c * W \tag{4.7}$$

where,

F_r = rolling friction [N],

F_d is the total draft force acting on the field-testing unit [N],

c = constant of rolling friction,

W = weight of the field-testing unit [N].

The rolling resistance force produced by the field-testing unit is 1.167 kN and the draft force produced is 30.708 kN, and total opposing force produced by the field-testing unit is 31.875 kN. Considering a Tractor unit traveling at 4.1 m/s having an overall transmission efficiency of 0.85, the total engine power required to pull the field-testing unit is 153.75 kW. Using the above calculation, a tractor unit with ≥206 hp is required to pull the field-testing unit attached with the subsoiler tool.

It was found from the analysis that, the field-testing unit withstands all the extreme case load scenarios. The results from the structural analysis were discussed in this chapter, along with machine efficiency and engine power requirement. CAD drawings were created for manufacturing of the field-testing unit. The next chapter describes the manufactured machine, field testing, and discusses results from the field test. Safe operating procedure is also drafted for the operation of the field-testing unit.

Chapter 5 Field testing

5.1 Summary

Field tests were conducted to verify operating conditions of the manufactured field-testing unit. Prototype hoe openers were used in a corn residue field to test the feasibility of the unit for evaluating the field performance of openers. The field measurements collected include soil and residue conditions, seeding depth, soil coverage, and furrow profile. The recorded soil depth was compared with the pre-set depths to determine the machines capacity to maintain operating depths. The operating procedure with safe operating conditions is discussed in this chapter. Additionally, SOP (safe operating procedure) for the field-testing unit is documented. This chapter describes the field tests and measurements, provides results to verify the field-testing unit according to the requirements.

5.2 Description of the manufactured machine

After verifying the structural components of the field-testing unit, CAD drawings were prepared for the assembly, subassemblies, and parts required for manufacturing. Figures A5.1 and A5.2 show components and dimensions of the mainframe. The testing unit was outsourced to a facility for manufacturing. Figure 5.3 shows the manufactured machine with additional components used to design the hydraulic system. A sheet metal plate with grooves is installed on the front portion of the hitch to hold hydraulic hose fitting when the machine is not in use. Clamps of 0.84-inch size are installed around the mainframe and hitch frame to hold the hydraulic hose for safer operation. Additionally, hydraulic stoppers are installed in all the three hydraulic cylinders to avoid any actuation of cylinders during transportation. Support plates are also installed to avoid any extensive vibrations from the mainframe and subframe. Figure 5.1 shows the mainframe, subframe and rocker arm of the field-testing unit. The mainframe is painted in white, whereas the subframe is red in color.

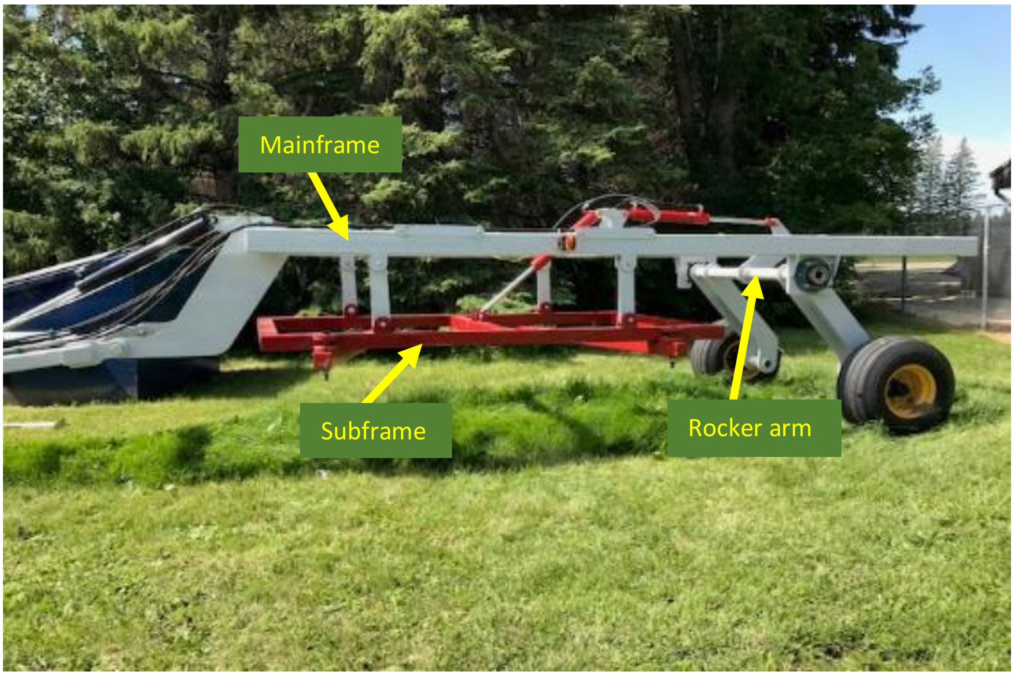


Figure 5.1 Manufactured field-testing unit

Figure 5.2 Gang angle adjustment mechanism connecting subframe and toolbar

Figure 5.3 Manufactured field-testing unit with groove plate (a), hydraulic stoppers (b) and support plates (c).

A total of six hydraulic hose fittings is used to connect the three hydraulic cylinders. Figure 5.2 shows the gang angle mechanism connecting subframe and toolbar with a 1-inch, grade 5 hex bolts. Gang angle adjustment is more convenient using this mechanism as the toolbar slides easily due to the pivoted subframe.

5.3 Field-testing unit setup

The test setup for the field-testing unit consists of an opener tool attached to the C-shank. The total height of the tool to be tested is 28 inches. Initially, the subframe hydraulic cylinder was retracted completely to get enough room for installing the tools. The tools were attached to the toolbar with a spacing of 18 inches. After completing the tool attachment, the field-testing unit was driven to the test site. A level gauge was set up on the mainframe to maintain the frame parallel to the ground. The hitch and rock arm hydraulic cylinders were extended to its maximum position. Based on the level gauge reading, alterations are made to both cylinders to keep the frame parallel to the ground.

a)

b)

Figure 5.4 a) Field-testing unit with extended front and back hydraulic cylinder, b) Field-testing unit with extended subframe for opener field test.

When the field-testing unit is parallel to the ground, the subframe cylinder is extended, and the depth of the tool is determined using a steel ruler. Figure 5.4 a) shows the field-testing unit with extended front and back cylinders, and b) shows the field-testing unit with the extended subframe. A part of the field was used to test the setup by performing a trial run to find depth accuracy for each set depths (0.5, 0.1,1.5, and 2.0).

5.4 Description of the field tests

The opener used for the testing was provided by Atom-Jet Industries. Figure 5.5 a) shows the opener attached to a C-type shank, and b) shows five openers attached to the field-testing unit. The tests were conducted in a research farm in Portage la Prairie, Manitoba in August 2018. The field had heavy corn residue with a weedy condition, as shown in Figure 5.6 a. The field conditions were tested to determine the optimal field conditions. The residue cover was measured with four different working depths of 0.5, 1.0, 1.5, and 2.0 inches (better crop production in these depths) with 5 replicates. Therefore, a total of 20 tests were performed in a randomized order, as shown in Figure A5.3 of the appendix. All tests were conducted at a constant travel speed of 10 km/h.

a) b)

Figure 5.5 a) Atom-jet opener, b) five openers attached to the field-testing unit.

Various data from field were collected to understand the field working conditions. The residue cover in the field was measured using the rope method (Chen et al. 2016). A 20-ft rope with marks spaced at 1 foot apart was laid out on the soil surface, as shown in Figure 5.6 b. A count was recorded at a mark if it coincided with a notable piece of crop residue. The residue cover (%) was determined as the number of the counts along the rope divided by the total number of marks on the rope. The surface residue was collected within a quadrant of 1 x 1 meter and oven-dried at 55 °C for 72 hours to determine the dry mass of surface residue (Chen et al. 2016). Figure 5.6 c shows the 1 x 1 Quadrant used for the experiment. Soil core samples of 50 mm in diameter and 54 mm in depth were collected and oven-dried at 105 °C for 24 hours to determine the soil moisture content and bulk density of the soil (Tessier et al. 1990). Figure 5.6 d shows the core sampler used in the experiment. All the field condition measurements were performed at 5 random locations across the field.

The field had a silty clay soil (46% clay, 49% silt, and 5% sand) with a 20.9% moisture content and 1.27 g/cm^3 dry bulk density as shown in Table 5.1. The moisture content and bulk density were suitable for field operations on this type of soil. The surface residue mass was 7534 kg/ha, which covered 61.1% of the field surface.

(a) (b)

Figure 5.6 a) Testing field plot; b) Residue cover.

(c) (d)

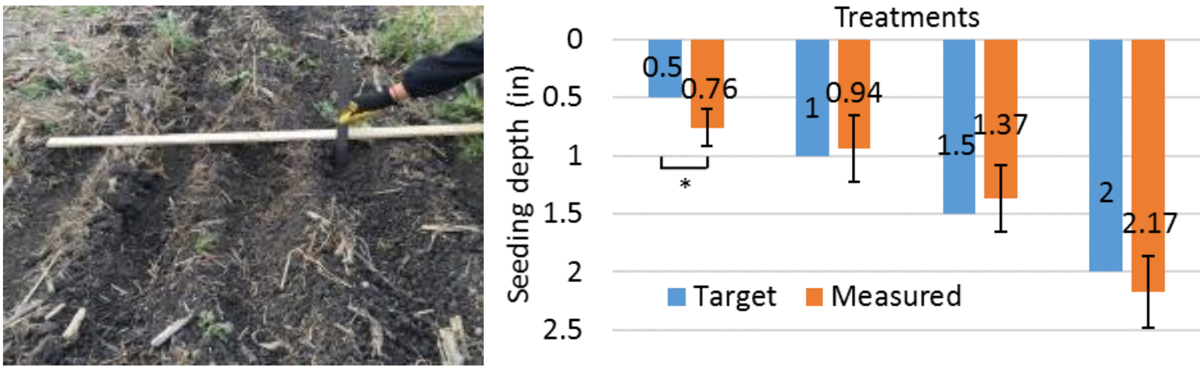
Figure 5.6. c) Testing field plot; d) Residue cover.

Table 5.1 Field condition results

Measurement	Value
Moisture (%)	20.9 ± 3.5
Bulk density (g/cm^3)	1.27 ± 0.13
Residue cover (%)	61.1 ± 10.9
Residue mass (kg/ha)	7534 ± 1800

Following the opener passage, the loosened soil in the furrow was manually brushed away to expose the furrow bottom. A wooden stick was placed and aligned with the original soil surface across the width of the furrow. The seeding depth was measured as the relative depth of a furrow bottom to the soil surface, as shown in Figure 5.7 a. This seeding depth is the theoretical depth assuming a seed would be placed at the bottom of a furrow and the loosened soil would be moved back and compacted in the furrow to its original surface level (neither seeds nor packer wheels were used in the tests). The measurement was replicated at three random furrows for each plot, which resulted in a total of 15 readings for each treatment.

The measured seeding depth was highly variable, ranging from 0.16 to 2.8 inches. The possible causes of the large variability in seeding depth were: 1) the presence of large quantities of corn residues and weeds in the field without seedbed preparation posed a suboptimal condition for the operation of the hoe opener; 2) the C-shank had a certain degree of flexibility due to its spring effect. The latter was clearly observed at shallow working depths, where the opener would occasionally bounce out of the soil surface at the travel speed of 10 km/h. The average seeding depths were statistically equivalent to the target values as shown in Figure 5.7 b. The results suggested that shallow working depths, such as 0.5 inch, should be avoided for a uniform seeding depth. The field-testing unit performed well in maintaining the pre-set operating depth.



(a) (b)

Figure 5.7 Seeding depth measurement (a) and results (b).

The relative depth of a furrow with loosened soil to the original soil surface was measured using the same method as measuring the seeding depth. The soil coverage of seed was calculated as the difference in height of a furrow with loosened soil and the seeding depth, i.e., the thickness of loosened soil layer above a seed as shown in Figure 5.8 a. The measurement was replicated at three locations for each plot with five furrows as samples, which resulted in a total of 75 readings for each treatment.

It was observed that the increase in working depth led to increase in the soil coverage of the furrows, as shown in Figure 5.8 b. The seed would have a soil coverage of 1.9 to 0.89 inches when the opener was operated at 2.0 and 1.5 inches respectively, which were significantly higher than that of 1.0 and 0.5 inches working depths. The soil coverage indicates the amount of soil that was thrown away from the furrow by the opener and the amount of soil falling back into the furrow. The results suggest that a large portion of the

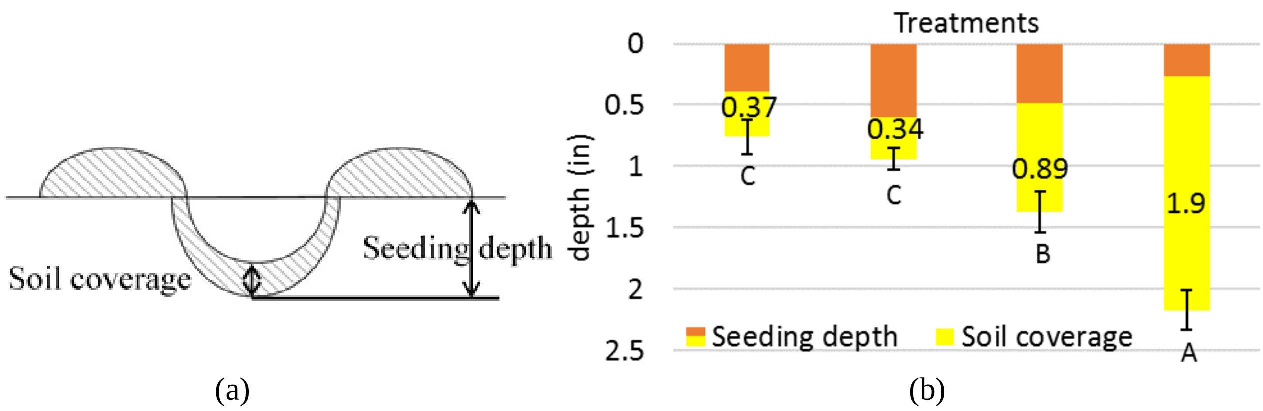


Figure 5.8 (a) Soil coverage, and (b) results.

loosened soil fell back into the furrow to cover seeds at deeper working depths of 1.5 and 2.0 inches, which were usually desired in terms of facilitating the seed emergence and early plant growth. Additionally, the furrow profile was recorded using a portable 3D Laser scanner (Sense, 3D Systems, Rock Hill, SC, USA). The details of the process and images are provided in the Appendix 5.

5.4.1 Conclusions

The following conclusions were drawn from the field tests;

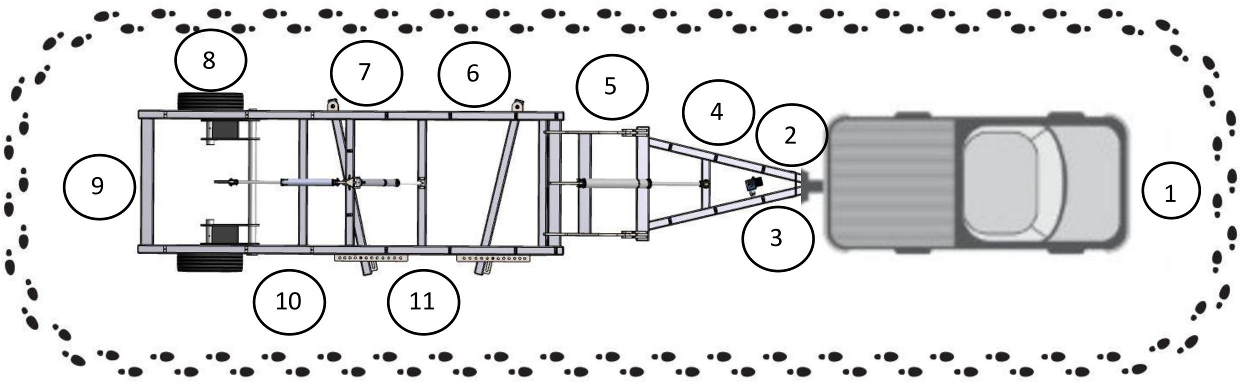
1. The field-testing unit has a high level of transportability, functionality, and testing capability, which warrants further studies on the performance evaluation of soil-engaging tools with the fiend-testing unit.
2. The field-testing unit satisfies all the requirements of the design and performed well during the field tests of the openers.
3. The hoe opener proved a good seeding tool in terms of achieving a target seeding depth and creating a sufficient soil coverage.
4. The seeding depths of 1.5 and 2 inches outperform two shallower depths of 0.5 and 1.0 inches in terms of the seeding depth and soil coverage.

5.5 Maintenance and safety of the field-testing unit

The field-testing unit was studied during the field tests for potential hazards and operating condition. Circle check and SOP (safe operating procedure) were used to define the safe operation of the unit.

5.5.1 Circle check

A circle check can be defined as a visual and/or physical inspection of a piece of equipment (e.g., truck, trailer, forklift, etc.). The process involves walking all the way around the equipment to make sure that there are no safety concerns regarding the vehicle. A circle check is generally completed at the beginning and end of the trip to ensure the safety of the field-testing unit and users (people operating or involved in the field tests). It was found that 843 agricultural related fatalities were reported between 2003-2012 (CAIR 2016). To prevent any fatalities, a circle check is recommended to be performed on the field-testing unit to handle and operate the unit safely. The process involves walking around the unit and a towing vehicle. The key safety areas of the field-testing unit are identified and marked in Figure 5.8. For example, the hydraulic stoppers should be securely placed on the pistons of the hydraulic cylinder. Ignoring to do so may result in leakage, breakage, or malfunction of the equipment during field operation. It is also important to record and report any problems to the concerned personnel immediately and not use the field-testing unit until the issue has been resolved. Table 5.2 shows the list of checks that need to be performed on the field-testing unit. Periodic maintenance check must be performed on parts of the field-testing unit like wheels, hub and drum assemblies, hydraulic cylinders and wheel bolts. A maintenance table containing the information related to the inspection required and replacement parts are shown in Table A5.1 of the appendix.



No. Area Yes No Details

Figure 5.9 Key safety areas during circle check of the field-testing unit

1 Is the tow vehicle in proper
working condition for

Table 5.3 List of visual check that needs to be performed during circle check

No.	Area	Yes	No	Details
1	Is the tow vehicle in proper working condition for towing?			
2	Is the hitch clear and in good condition?			
3	Is the jack lowered / raised properly?			
4	Are the hydraulic hoses secured in the groove plate?			
5	Are the hydraulic stoppers secured in position?			
6	Are the frame locks secured?			
7	Is the subframe hydraulic cylinder completely retracted?			
8	Is the tire pressure and tread wear good?			
9	Is the towing light working properly and is it secure?			
10	Are there any leaks in the hydraulic system?			
11	Are the gang bolts secured?			

Table 5.4 List of visual check that needs to be performed during circle check

Area Yes No Details

5.5.2 SOP (Safe Operating Procedure)

The SOP documented for the field-testing unit is intended to provide general safety guidelines for the operation of the unit. Potential hazards during the operation of the unit are identified to constrain any safety hazard related to the unit. The document includes job hazard identification, job steps for circle check, towing, field-testing of the unit, and recommended tools for successful operation of the unit. The following document shows the SOP for field-testing unit:

JOB TITLE - HAULING AND SAFETY DURING OPERATION of THE FIELD-TESTING UNIT

JOB DESCRIPTION – This guideline describes the hauling and operating the field-testing unit in the field safely.

JOB HAZARD IDENTIFICATION

Personal injury

- Muscle pull/strain, slip, runover, crushing injuries, trip and fall.

Vehicle/equipment

- Equipment accidents, equipment failure, struck by hydraulic operation.

Environmental

- Visibility, weather, working alone, variable terrain.

JOB STEPS / GUIDELINES

1. **CIRCLE CHECK**

   - The operator should conduct a circle check on the towing vehicle and field-testing unit to detect the equipment deficiencies and ensure that safety related defects and other necessary repairs or deficiencies are corrected prior to utilizing the unit.
   - After circle check is completed, fill out circle check documentation.
   - The operator can only perform repairs or adjustments that they can perform completely and have other repairs performed by qualified personnel.

2. **TOWING THE FIELD-TESTING UNIT**

   - After circle check is completed ensure unnecessary attachments are dismounted.
   - Check security of hitch and hydraulic lines.
   - When attaching the towing vehicle to the field-testing unit it is recommended that the operation be performed by two people.
   - Guide must always be in view of the operator and use predetermined method of communication (e.g. hand signals, verbal, horn etc.).
   - Ensure area is clear of people, and obstructions.
   - Ensure that there is no loose load on the field-testing unit and secure the tool load.
   - Ensure hitch is free of loose debris and screw jacks are lifted and stored correctly for transport.
   - Ensure wheels are properly blocked (with connecting chains to prevent loss of chock blocks) prior to disconnecting unit from assisting unit.

3. FIELD-TESTING

- After arriving at the test site, a walkaround of the field-testing unit is recommended to detect any anomalies.
- After attaching the field-testing unit safely to the tractor, it is recommended to turn off the tractor before installing the require tools on the toolbar to avoid any fault operation of the hydraulic system.
- The users accompanying field-testing unit are required to stay at a safer distance during hydraulic operation.
- A circle check needs to be performed after the field tests to ensure all the components of the field-testing unit are safe.

RECOMMENDED TOOLS / EQUIPMENT

Tools

- Level gauge, wrench set, steel rulers, hammer, WD-40(to remove highly torqued nuts) and measuring tape.

Miscellaneous

- First aid kit, markers/pens, notepad, flags, duct tape, wheel blocks/chocks
- Please refer to the type of field tests for any other type of equipment or tools required.

RELATED SAFE OPERATING PRACTCES / MANUALS

(Please refer to the following keywords for further information on safe practices)

- Agricultural equipment safety – safe work Manitoba, Vehicle and Machinery Safety on the Farm – Canada Safety Council, Mobilization of tractors and light trucks, backing up a trailer, hitch safety, safe use of hand tools,.

Date S.O.P prepared 25 / 07 / 2019
Prepared by – Sumanth Kuntavalli

Chapter 6 Conclusion and recommendations

6.1 Conclusion

This research discusses the design and testing of a field-testing unit. The customer inputs are obtained, and Quality function Development (QFD) methods are used to obtain functional requirements of the unit. The functional requirements are converted to technical specifications based on their similarity factor. The main task was to develop a machine to satisfy all the obtained customer requirements. A house of quality (HoQ) is formed to link the functional requirements and technical specifications. The relative score between the two are calculated to prioritize the generation of machine concepts. In order to find the best solution, two different concepts of the machine are generated and scored based on the importance factor of the functional requirements. The machine concept with the highest total score is selected for the design. HoQ is also used to select different components and power requirements for the field-testing unit. After finalizing the components, CAD models and manufacturing drawings are produced in the SolidWorks software.

The maximum draft forces for selected tools are estimated, and they are used as the design loads to perform the structural analysis of the field-testing unit. Ansys 18.0 solver is used to conduct the structural analysis. Meshing and constraints are applied after importing the CAD model into the software. Upon analysis, it was found that the machine components are safe for the given design loads. The toolbar was modified with additional gussets to withstand the load of the given tool. After manufacturing the field-testing unit at an outsourced facility, the field-testing unit was tested in a field in Portage La Prairie, Manitoba. Prototype openers were obtained from Atom-jet industries, Brandon, and they were attached to toolbars of the field-testing unit. All the field tests were conducted at a constant speed of 10 km/h for four different depths of 0.5, 1.0, 1.5, and 2.0 inches. A total of 20 test runs were performed. Data for the crop residue coverage and soil furrow profile were collected and compared among different working depths of the openers. It was found that the field-testing unit performed well in the field tests. The field-testing unit can support any tools ranging between the heights of 14 inches to 63 inches, and it can be safely operated at various working depths and travel speeds. In conclusion, the field-testing unit was successfully designed, developed and tested for its function. Table 6.1 shows the checklist with features used to achieve the customer requirements.

Table 6. 1 Check list and features for the achieved requirement

No.	Requirement	Yes/No	Features / Comments
1	Supporting variable tool length (15-36 inches)	Yes	40-inch motion range
2	High travel speeds (up to 80 km/h on highways)	Yes	Good year Fs-24 tyres
3	Working in high residue conditions (up to 8 inches)	Yes	10-inch ground clearance
4	Highway transportation	Yes	Universal hitch mechanism
5	Safety during transportation	Yes	Support plates, hydraulic stoppers and groove plates
6	Tool perpendicular to the ground	Yes	Adjustable using front and rear hydraulic cylinder
7	Tool gang angle flexibility	Yes	Gang angle (0 – 22 degrees)
8	Having ballast holders	No	Commercial ballast holders available
9	Different working depths	Yes	40-inch motion range
10	Parking stability	Yes	Manual swivel jack installed
11	Operation with hydraulic cylinders	Yes	Three hydraulic cylinders for easy operation

6.2 Contributions

The contributions of this research are as follows:

1. A field testing-unit for agricultural tool testing was developed: methods such as HoQ was used to determine functional and technical requirements for the machine. Multi-criteria methods were used to finalize parts of the unit.

2. Field testing methods are implemented on the unit to validate the performance in field conditions.
3. Safe operating procedure and circle check for the developed field-testing unit are developed for the operational safety of the unit.
4. A conference paper is published related to the research (Development of a field-testing unit for vertical tillage (VT) and seeding, paper number: 1801237, 2018 ASABE Annual International Meeting, Detroit, Michigan)

6.3 Recommendations

The following recommendations are made for future studies:

1. Further study of the field-testing unit can be conducted by attaching dynamometers to the hitch and toolbars to determine the actual forces acting on the field-testing unit.
2. Portable Laser profilers can be directly attached to the rear of the field-testing unit to obtain real-time data of the soil profile.
3. A pair of 4x6 toolbars can be manufactured and attached to efficiently test heavy-duty tools like subsoilers and avoid extensive damage to the frame.
4. The depth adjustments of the hydraulic cylinders can be integrated with the electronic systems of the tractor to change the operating depth more precisely.
5. A depth measurement scale and level gauge can be attached to the field-testing unit to help in maintaining the frame parallel to the ground.
6. The vibrations occurring on the frame can be studied for different tools and parameters using a vibration meter.
7. Additional side frames can be added to the mainframe to support seed and fertilizer storage bins to test different seeding equipment.
8. Roller mounts can be attached to the rear of the field-testing unit to support testing of different rollers.

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page 16: keyword: hoe openers, Atom-jet, seed openers.

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Appendix Chapter 3

Table A3.1 Numbered description of the assembly and subassemblies (Concept A)

level	No.	Part No.	Description	QTY	Supplier
Assembly	1	19100	Field testing unit-1	1	Custom part
Subassembly	2	19010	Hitch frame_1	1	Custom part
	3	19020	Mainframe_1	1	Custom part
	4	19030	Toolbar_1	2	Custom part
	5	19040	Wheel frame_1	1	Custom part
Child parts (Hitch frame)	6	19011	Hitch mount 3H	1	Pj trailers
	7	19012	support plate ½”	2	Custom part
	8	19013	4/4” frame_1main	1	Custom part
	9	19014	Frame support	2	Custom part
	10	19015	Pin support_4	4	Custom part
	11	19016	4/4” frame rear	1	Custom part
	12	19017	Support between_3	4	Custom part
	13	19018	4/4” side frames	2	Custom part
Child part (Mainframe)	14	19021	Wheel frame Support	2	Custom part
	15	19022	4/4” frame	1	Custom part
	16	19023	Hitch support	2	Custom part
	17	19024	4/4” front frame	1	Custom part
	18	19025	Spring drawbar support	1	Custom part
	19	19026	Hyd support	2	Custom part
	20	19027	Centre 4/4” frame	1	Custom part
	21	19028	Rear 4/4” frame	1	Custom part

Table A3.1 Numbered description of the assembly and subassemblies (Continued…)

level	No	Part no	Description	QTY	Supplier
Child part	22	19029	Tool holder plate_2	8	Custom part
(Mainframe)	23	19030	Tool holder positioning bolt	16	Fastenel
Child parts (Toolbar)	25	19031	4/6” toolbar frame	4	Custom part
	26	19032	Pivot pin support	2	Custom part
	28	19033	1” Pivot pin	4	fastnel
Child parts (wheel support)	29	19041	Mainframe bracket	2	Pj trailers
	30	19042	4” tube	2	Custom part
	31	19043	Rocker arm support frame	2	Custom part
	32	19044	Wheel hub mount	2	Custom part
	33	19045	Support frame	1	Custom part
Other parts	40	18064	Hyd cyl_1 3*15	1	Princes auto
	41	18065	Spring drawbar	2	fastnel
	42	18066	Wheel hub	2	versatile
	43	18067	rim	2	versatile
	44	18068	Fs 24 tyre	2	versatile

Table A3.3 comparison of features used in concepts and selected commercial machines

	Machine A	**Machine B**	**Machine C**	**Concept A**	**Concept B**
Hitch type	Lunette ring	Lunette ring	Lunette ring	Universal hitch	Universal hitch
Toolbar size (inches)	4x4	4x4	4x5	4x4	4x4
Transportation wheel	FS-24	AD2	SL-15	FS-24	FS-24
Hitch control	Hydraulic	Manual	Manual	Manual	Hydraulic
Mainframe type	Single frame	Single frame	Single frame	Single frame	Parallel linkage
No. of toolbars	2	4	2	4	2
Depth control	hydraulic	hydraulic	manual	hydraulic	Hydraulic
Total width (meters)	5	3.5	4	2.2	2.4
Total weight (kg)	1890	1225	980	855	1375

Table A3.4 Criteria for rating functional requirement

Support different tools	1	Support single type of tool
	2	Support 2 types of tool
	3	Support 2 tools + rear roller support
	4	Support multiple tools + gang
	5	Support all selected tools + rear roller + gang
Travel at high speed	1	<10km/h
	2	10 – 15 km/h
	3	10 - 25 km/h
	4	10 – 60 km/h
	5	Travel at determined speed (80km/h)
Work in field conditions	1	No field clearance
	2	-
	3	Work with min clearance (5inches)
	4	-
	5	Work with max clearance (10 inches)
Travel on highways	1	Cannot travel on highways
	2	-
	3	Can travel on highways (<60 km/h)
	4	-
	5	Can travel on highways (>60 km/h)

Table A3.4 Criteria for rating functional requirement (continued…)

Safety during transportation	1	No safety lights/width limit not satisfied
	2	-
	3	-
	4	-
	5	Safety lights/satisfies MPI width limits
Tool perpendicular to ground	1	Tool not perpendicular to ground
	2	-
	3	-
	4	-
	5	Tool perpendicular to ground
Gang angle flexibility	1	Cannot change gang angle
	2	0 – 5 degrees
	3	0 – 10 degrees
	4	0 – 15 degrees
	5	Up to 23 degrees
Ballast holders	1	Does not have ballast holders
	2	-
	3	-
	4	-
	5	Have ballast holders

Table A3.4 Criteria for rating functional requirement (continued…)

Different working depths	1	2-4 inches
	2	8 inches
	3	10 inches
	4	15 inches
	5	>20 inches
Parking stability	1	Trailer jack not available
	2	-
	3	-
	4	-
	5	Trailer jack available
Hydraulic cylinder operation	1	No hydraulic available
	2	Manual depth control
	3	Hydraulic depth control
	4	Hydraulic depth and hitch control
	5	all variable features operated by hydraulics

Table A3.5 requirements and concerns to select the width of the field-testing unit.

	Requirement	Factor	Concern
1	The field-testing unit needs to be transported via highways to different locations for testing.	Provincial road rules of Manitoba, (special permit required if vehicle exceeds 2.6 meters)	The width of the machine should stay within the stated limit.
2	No track marks from tractor/field-testing unit (tire indentation on the ground) should be on the furrow profile after/before testing.	The tyre sizes of the tractors are large (12-24 inches).	The tires of the field-testing unit should be outside the frame to avoid track marks.

Different tires from commercial agricultural machines were studied, and the most common type of tires was selected for the field-testing unit. The tyre selected was provided by the participating company for manufacturing of the field-testing unit.

Table A3.6 Commercial machine tire comparison.

Machine	Tyre used	Dimension (width)	Comments
Versatile offset disk model- TD650N	Good year FS-24 340/60R16.5	12.70 inch	• Radial construction • Large contact area • Round shoulders • Highway appearing tread design • Low rolling resistance • Long life and smooth operation • Very good stability
Field King FKEHDHH-26-24	Good year FS-24 360/65R17.5IMP	14.70 inch	
John-Deer VT 17 series	Highway Implement 13.50-15FI C	13.50 inch	• Low rolling resistance • Excellent protection against punctures • Smooth running on the road • Long life

Gang angle calculation for the toolbar

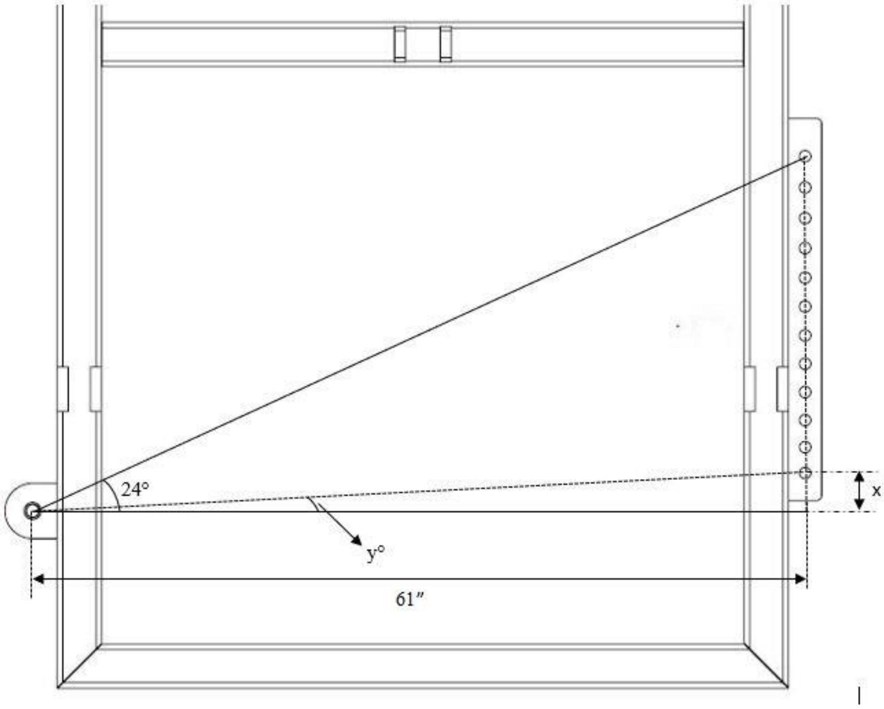


Figure A3.1 sub frame showing the angle between pivot and bolted part

The holes on the gang angle plate are designed such that they are 2 degrees apart from the refence point. When the toolbar is bolted to the first hole the angle between toolbar and subframe is 0 degrees, and for the second hole, it is 2 degrees and so on. The location of the holes is calculated using following equation:

$$\tan y° = \frac{x}{61"} \qquad (3.1)$$

Where x is the distance of the hole from the reference line, and y is the angle form the reference line. The position of holes calculated based on the above equation is summarized in Table A3.7.

Table A3.7 Hole placement table.

Adjustment	**Angle (Y°)**	**Distance of center of hole from refence line (x-inch)**
Hole 1	0	2.13”
Hole 2	2	4.26”
Hole 3	4	6.4”
Hole 4	6	8.51”
Hole 5	8	10.76”
Hole 6	10	12.97”
Hole 7	12	15.21”
Hole 8	14	17.49”
Hole 9	16	19.82”
Hole 10	18	22.20”
Hole 11	20	24.64”
Hole 12	22	27.16”

Hydraulic cylinder

Criteria for the selection of the driving power were selected in 2 steps. The first step was to compare the available mechanisms with their power requirement and power source available in the tractor (as the field-testing unit will be attached to the tractor). The second step was to compare the driving power with its possible uses (farm-machinery). Finally, the selected driving power is compared with the commercial machines to verify the selections.

From Table A3.8, manually operated spring bars cannot be used for our requirement as the total weight of the testing-unit is over 1000 Kgs. Linear actuator motors are used for light applications due to its portable and silent (does not make noise) operation. Hydraulic actuators are extensively used in agricultural applications. Hydraulic couplers are already provided in the tractors, which makes it easier for the use to install and operate the mechanism. Upon studying the more agricultural tillage machines, it was found that hydraulic cylinders are used for all the applications like moving the frame, adjusting the toolbar angle and hitch adjustments. Table A3.8 shows the commercial machines and uses of the hydraulic cylinders for operation.

Table A3.8 Different driving power comparison.

	Driving power	**Power source (required)**	**Power source (available in the tractor)**	**Possible applications**
1	Hydraulic actuator	Hydraulic pump / couplers	Hydraulic couplers	Used in heavy duty applications such as cranes, forklifts, agricultural machineries, industrial applications.
2	Electric Linear Actuator Motor	12 V DC	12 V DC	They are used in opening and closing dampers, locking doors, braking machine motions(car), etc.
3	Manually operated spring bar	Manpower	-	Used for lighter and small-scale applications where large weights are not involved.

Based on the selection criteria, it was finalized to use hydraulic actuators based on two factors. First, the extensive use of hydraulic actuators in the field of agricultural machinery guaranteed the functioning of the machine. The second factor was that the tractors are already built with hydraulic couplers, making it the best possible drive force. The stroke length required for the hydraulic cylinders and the mounting distance was calculated from the CAD model and are listed in Table A3.9, hydraulic cylinder locations are shown in Figure A3.2

Table A3.9 Stroke length and mounting distance

Hydraulic cylinder	Stroke required	Mounting distance	Hydraulic cylinder available in market
Cylinder 1	10-inches	54-inches	4-inch bore 30-inch stroke
Cylinder 2	20-inches	22-inches	3-inch bore and 20-inch stroke
Cylinder 3	18-inches	38-inches	3-inch bore and 20-inch stroke

Table A3.10 Hydraulic cylinders used in commercial machines and their applications

No.	Commercial machine	No of hydraulic cylinders used	Application
1	Versatile-Vertical tillage - Viking	8	Hitch operation, folding / unfolding of frames, and mainframe height adjustment.
2	John-deer 2230FH Field Cultivators	11	Hitch operation, rear attachments, folding unfolding of frames and height adjustment.
3	Field King FKEHDHH-26-24	3	Raise / lower mainframe, roller basket operation.
4	Case III – Heavy offset 790	2	Depth control and levelling.
5	KUHN Excelerator 8005	7	Hitch operation, folding / unfolding of frames, depth control, and roller basket.

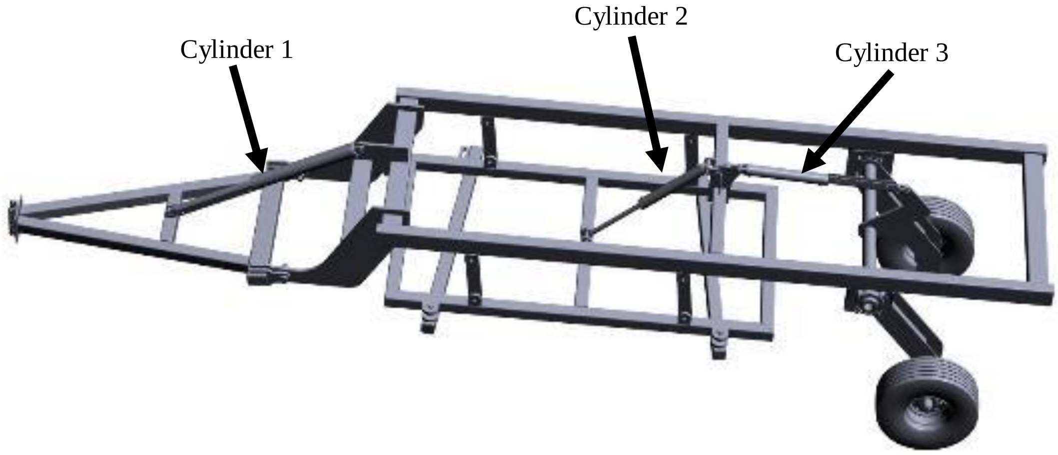


Figure A3.2 location of hydraulic cylinders

Hydraulic cylinders available in the market were studied to select the size of the hydraulic cylinder. It was found that only certain specifications are available for the stroke and bore of the cylinder combinations. The cylinders which meet the stroke length and mounting distance was cross-referenced with the commercial machine cylinders and selected. The selected cylinders are shown in Table A3.9

Safety lights

The lights were scored as 1 and 0. The score was assigned as 1 if the lights (A, B, and C) meet the criteria and 0 if the criteria are not met. As shown in Table A3.11 light C has the highest score of 3, and it was selected for the design.

Table A3.2 Summary of safety lights selected for the design

	Model	**Power source**	**Fixture type**
A	C742 LED Submersible trailer light kit	12v	Fixed
B	Clazer C6304 wireless LED towing light kit	Battery	Magnetic
C	Tow smart 80 in. under magnetic towing lights	12v	Magnetic

Table A3.11 Criteria and ranking of the selected lights

Criteria	**A**	**B**	**C**
Use existing power source from the tractor	1	0	1
Easy attachment and detachment	0	1	1
Price range (<100$)	1	1	1
Total (Rank)	2 (2)	2 (2)	3 (1)

Rocker arm calculations

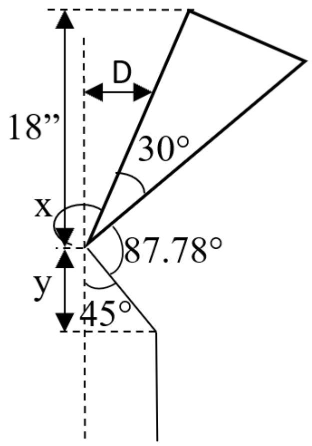


Figure A3.3 Line diagram of the rocker arm

In Figure A3.3, x is the displacement of rocker arm in radians, y is the displacement of support plate in inches, the vertical length of rocker arm is 18 inches. Using geometry, the displacement (D) of rocker arm in inches can be related to displacement (x) of the same in degrees using following Equation:

$$D = 18 * \tan x \qquad \text{(E3.1)}$$

Or

X can be calculated using Equation E3.2:

$$x = \tan^{-1}\left(\frac{D}{18}\right) \qquad \text{(E3.2)}$$

Also using geometry, the change in 'x' will displace the support arm and can be related using Equation E3.3:

$$y = \cos(45 + x) * 31 \qquad \text{(E3.3)}$$

Using the above equations, the total displacement is calculated and summarized in table A3.12.

Table A3.12 Displacement of hydraulic cylinder and rocker arm

Displacement of hydraulic cylinder (D) [inches]	Displacement of Rocker arm (x) [degree]	Displacement of support plate (y) [inches]
1	3.18043	20.6740
2	6.34138	19.3691
3	9.46410	18.0221
4	12.5311	16.6470
5	15.5270	15.2577
6	18.4384	13.8677
7	21.2545	12.4891
8	23.9670	11.1326
9	26.5700	9.80741
10	29.0600	8.52077
11	31.4355	7.27832
12	33.6964	6.08410
13	35.8444	4.94074
14	37.8821	3.84963
15	39.8130	2.81118
16	41.6413	1.82496
17	43.3716	0.88994
18	45.0084	0.00459

From the above table, one can observe that at D=18 inches and 45°, the displacement of support plate tends to zero which means that the testing rig is at its bottom most position where as at D=1, the rig is at its top most position. A stroke of 18 inches is required to adjust the testing rig to top and/or bottom most position. However, due to slight angle difference during the stroke the connecting rod has to cover some distance (negligible <1-inch) to achieve higher or lower position. So, a hydraulic cylinder with a stroke of 20 inches is desirable for this design.

Appendix Chapter 4

Draft force

The tool parameters were selected from the ASABE standard draft parameter table as shown in Table A4. 1(Agricultural Machinery Management Data, 1999).

Table A4. 1 ASABE standard draft parameter table

Implement	SI Units				English Units				Soil Parameters			Range
	Width Units	Machine Parameters			Width Units	Machine Parameters						
		A	B	C		A	B	C	F_1	F_2	F_3	±%
MAJOR TILLAGE TOOLS												
Subsoiler/ manure injector												
narrow point	tools	226	0.0	1.8	tools	129	0.0	2.7	1.0	0.70	0.45	50
30 cm winged point	tools	294	0.0	2.4	tools	167	0.0	3.5	1.0	0.70	0.45	50
Moldboard plow	m	652	0.0	5.1	ft	113	0.0	2.3	1.0	0.70	0.45	40
Chisel plow												
5 cm straight point	tools	91	5.4	0.0	tools	52	4.9	0.0	1.0	0.85	0.65	50
7.5 cm shovel/ 35 cm sweep	tools	107	6.3	0.0	tools	61	5.8	0.0	1.0	0.85	0.65	50
10 cm twisted shovel	tools	123	7.3	0.0	tools	70	6.7	0.0	1.0	0.85	0.65	50
Sweep plow												
primary tillage	m	390	19.0	0.0	ft	68	5.2	0.0	1.0	0.85	0.65	45
secondary tillage	m	273	13.3	0.0	ft	48	3.7	0.0	1.0	0.85	0.65	35
Disk, harrow, tandem												
primary tillage	m	309	16.0	0.0	ft	53	4.6	0.0	1.0	0.88	0.78	50
secondary tillage	m	216	11.2	0.0	ft	37	3.2	0.0	1.0	0.88	0.78	30

The calculated draft force with selected variables are shown in Table A4. 2 a, b, c and d for subsoiler, sweep plough, VT disk and opener. The highest value variable was considered for all the selected tools to calculate the force in the maximum loading condition.

Table A4. 2 draft force calculations for selected tools.

D=Fi[A+B(S)+C(S)^2]WT		Units
Fi	1	-
A	226	-
B	0	-
S	8	km/h
C	1.8	-
W	1	tool
T	30	cm
		-
Subsoiler =	**10,236**	**N**

a)

D=Fi[A+B(S)+C(S)^2]WT		Units
Fi	1	-
A	390	-
B	19	-
S	20	km/h
C	0	-
W	1.42	m
T	10	cm
		-
Sweep plough =	**10,934**	**N**

b)

D=Fi[A+B(S)+C(S)^2]WT		Units
Fi	1	-
A	309	-
B	16	-
S	10	km/h
C	0	-
W	1.42	m
T	20	cm
		-
VT Disk =	**13,320**	**N**

c)

D=Fi[A+B(S)+C(S)^2]WT		Units
Fi	1	-
A	500	-
B	0	-
S	10	km/h
C	0	-
W	1	rows
T	7.6	cm
		-
Opener =	**3,800**	**N**

d)

Rolling resistance

The rolling coefficient is considered as 0.08 for tyre on solid sand, gravel loose worn, soil medium hard as shown in Table A4. 3 (Engineering Toolbox, 2008).

Table A4. 3 Rolling resistance coefficient for different tires.

Rolling Resistance Coefficient		
c	c_l *(mm)*	
0.001 - 0.002	0.5	railroad steel wheels on steel rails
0.001		bicycle tire on wooden track
0.002 - 0.005		low resistance tubeless tires
0.002		bicycle tire on concrete
0.004		bicycle tire on asphalt road
0.005		dirty tram rails
0.006 - 0.01		truck tire on asphalt
0.008		bicycle tire on rough paved road
0.01 - 0.015		ordinary car tires on concrete, new asphalt, cobbles small new
0.02		car tires on tar or asphalt
0.02		car tires on gravel - rolled new
0.03		tires on cobbles - large worn
0.04 - 0.08		tire on solid sand, gravel loose worn, soil medium hard
0.2 - 0.4		car tire on loose sand

Table A4.4 Constrains assigned to parts of field testing-unit

Part no	**Part name**	**Fastener**	**Support type**
18011	Hitch mount 6H	pin	Fixed support
18017	Support plate_21	pin	Pin support
18021	Support plate 1”	pin	Pin support
18025	Subframe pin support	pin	Pin support
18027	Hyd support_1	pin	Pin support
18028	Hyd support_2	Pin	Pin support
18034	Subframe_pin support	Pin	Pin support
18036	Pivot supports	bolt	Bolted support
18035	1” gang angle plate	bolt	Bolted support
18045	3” Wheel hub support	bolt	Fixed support
18053	1” pivot tube	bolt	Bolted support
18062	Hyd cyl_1 3*20	Pin	Hinged support
18063	Hyd cyl_2 3*20	Pin	Hinged support
18064	Hyd cyl_3 4*30	pin	Hinged support

Part no	**Part name**	**Fastener**	**Support type**
18011	Hitch mount 6H	pin	Fixed support
18017	Support plate_21	pin	Pin support
18021	Support plate 1”	pin	Pin support
18025	Subframe pin support	pin	Pin support

Moment calculations

Due to the absence of tool in the model, the draft force at the tip of the tool needs to be transferred to the mounting plates in the toolbar.

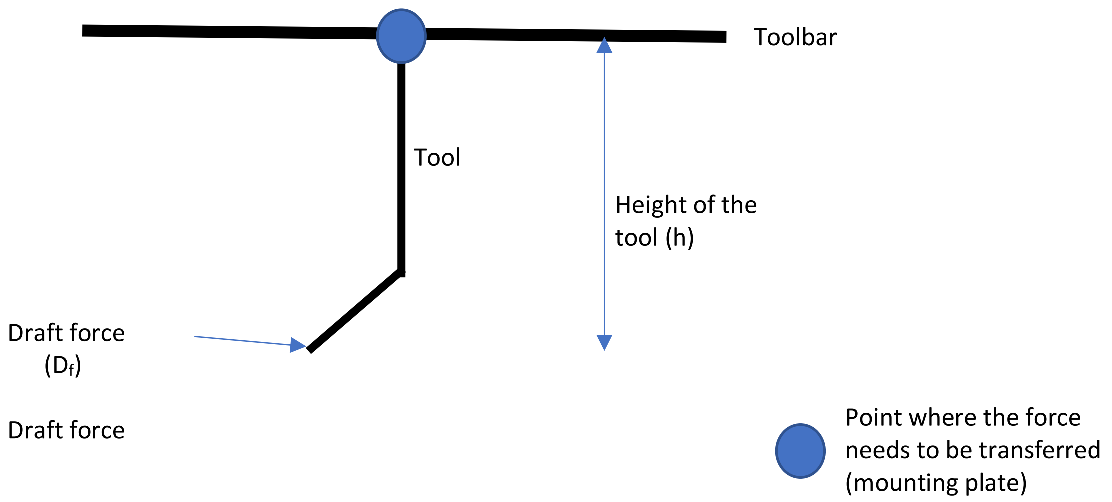


Figure A4.1 line diagram for moment calculation

Moment induced due to shifting of force is:

$M_d = D_f \times d$

For subsoiler,
$D_f = 10.2$ kN
h = 0.86 m

for VT disk,
$D_f = 13.3$ kN
h = 0.83 m

M_d (subsoiler) = 8.8 kN-m

M_d (VT disk) = 11 kN-m

Modified toolbar

Modified toolbar with additional support gussets and increased thickness is shown in Figure A4.2.

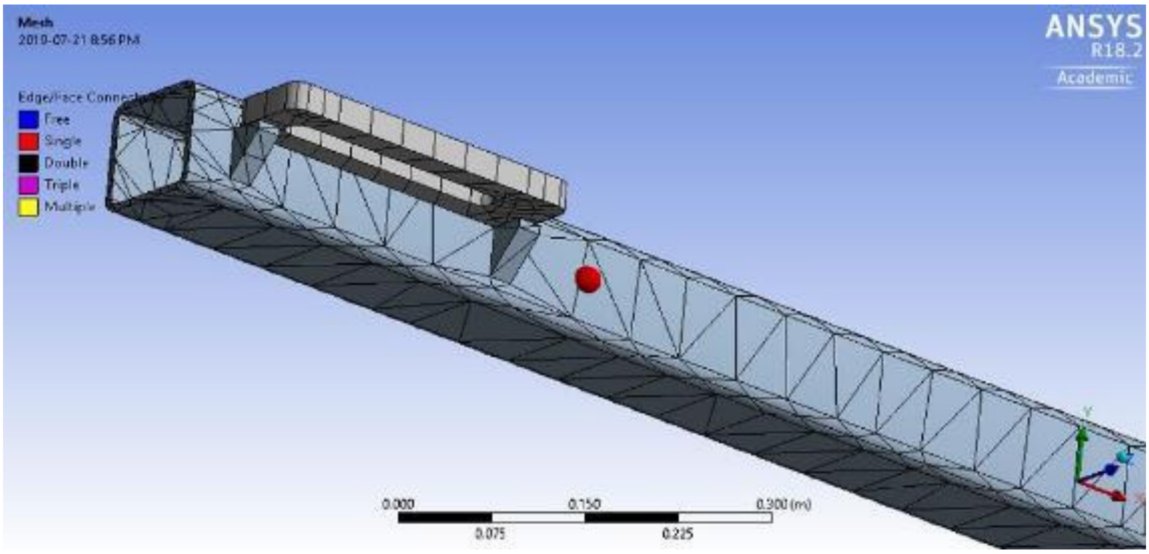


Figure A4. 2 Modified toolbar

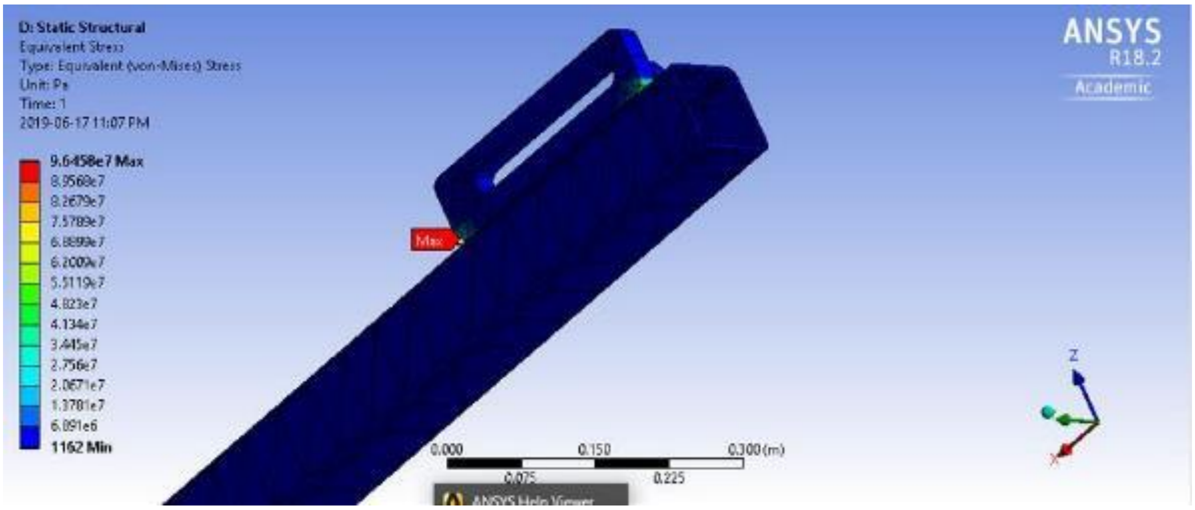


Figure A4. 3 Modified toolbar showing considerably less stress after modifications

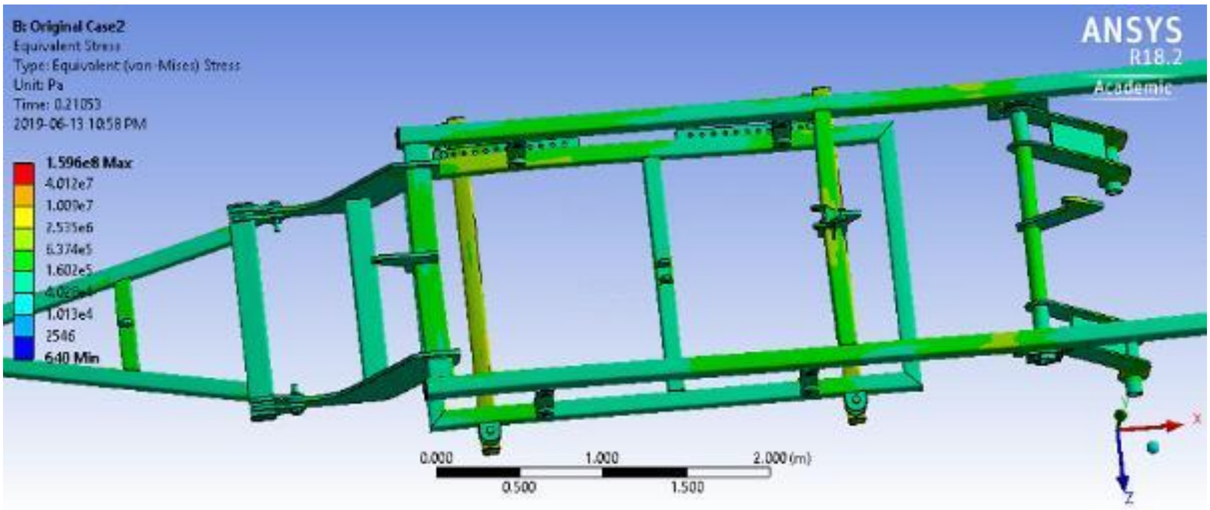


Figure A4. 4 Stresses in case 2

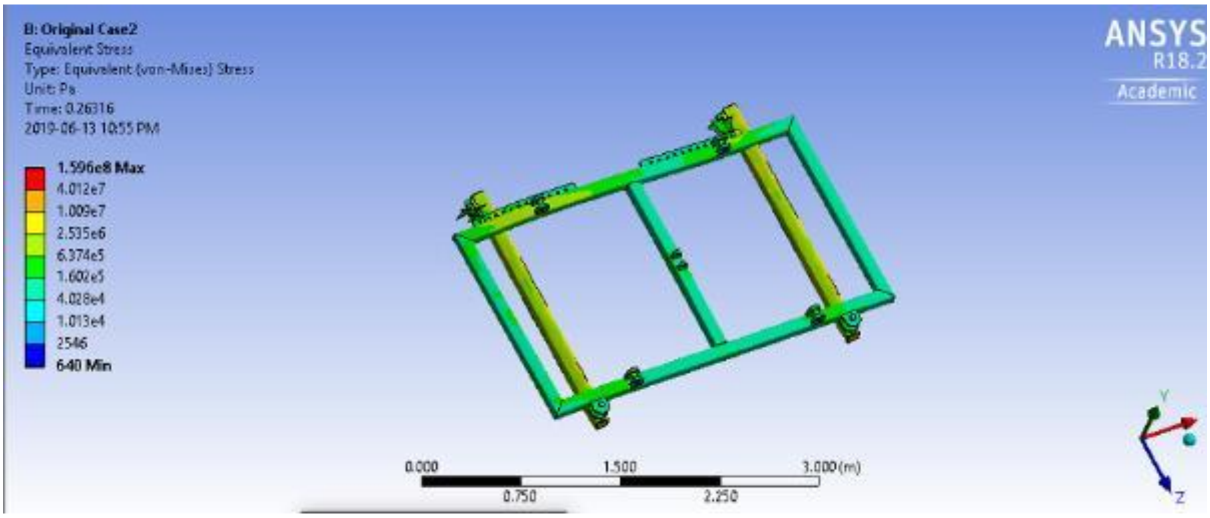


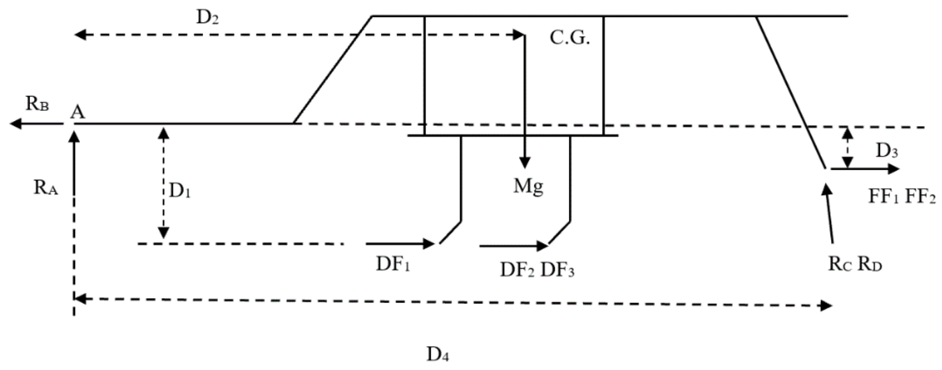
Figure A4. 5 Stress for Case 2: subframe assembly of the field-testing unit

Figure A4. 5 Stress for Case 2: subframe assembly of the field-testing unit

Calculation of Reaction forces on the machine

The free body diagram of the entire machine is shown below:

Front view



Top view

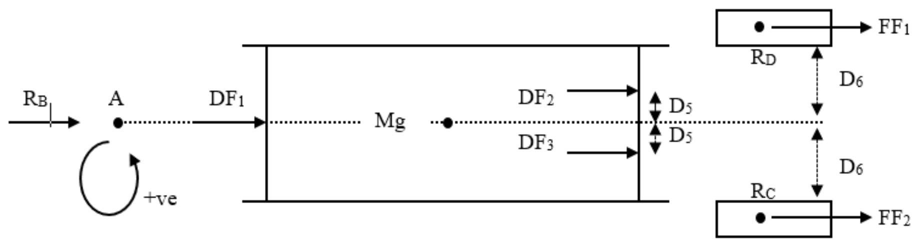


Figure A4. 6 line diagram

The equilibrium equations for the given FBD are as follows:

The net forces in X and Y direction=0

The net Moment in X-Y plane at point A=0

Hence we have,

$$\sum F_Y = 0$$

$$Mg = R_A + R_B + R_D \; Equation - A4.1$$

$$\sum F_X = 0$$

$$R_B = DF_1 + DF_2 + DF_3 + FF_1 + FF_2 \; Equation - A4.2$$

$$\sum M@A = 0 \qquad +\text{ve}$$

X-Y plane

$$DF_1 * D_1 + DF_2 * D_1 + DF_3 * D_1 - Mg * D_2 + R_C * D_4 + R_D D_4 + FF_1 * D_3 + FF_2 * D_3 = 0\ Equation - A4.3$$

Simplifying the above equation

We get

$$(DF_1 + DF_2 + DF_3) * D_1 + \ (R_C + R_D) * D_4 + (FF_1 + FF_2) * D_3 - Mg * D_2 = 0$$

Now

$$FF_1 = Fr * R_C$$

$$FF_2 = Fr * R_D$$

Where

$$F_r = Rolling\ Resistance\ on\ wheels$$

Hence we have,

$$FF_1 = 0.08 * R_C$$

$$FF_2 = 0.08 * R_D$$

Substituting the values in the equation A4.3

$$(DF_1 + DF_2 + DF_3) * D_1 + \ (R_C + R_D) * D_4 + (0.08R_C + 0.08R_D) * D_3 - Mg * D_2 = 0\ Equation - A4.3$$

Simplifying the above equation, we get

$$(R_C + R_D) * [D_4 + 0.08 * D_3] = \ -(DF_1 + DF_2 + DF_3) * D_1 + Mg * D_2\ Equation - A4.3$$

The machine is symmetrical about X-Z plane and loading is also symmetrical on rear tool bar

Hence,

$$R_C = R_D$$

Say R_w= Reaction on a wheel = $R_C = R_D$

Equation A4.1 becomes

$$\boldsymbol{R_A + 2R_W = Mg}$$

Equation A4.2 becomes

$$-R_B + 0.08 * R_C + 0.08 * R_D = -DF_1 - DF_2 - DF_3$$

$$\boldsymbol{-R_B + 0.16R_W = -DF_1 - DF_2 - DF_3}$$

Equation A4.3 becomes

$$\boldsymbol{(R_w) * 2 * [D_4 + 0.08 * D_3] = -(DF_1 + DF_2 + DF_3) * D_1 + Mg * D_2}$$

$$R_W * 2 * [D_4 + 0.08 * D_3] = -(DF_1 + DF_2 + DF_3) * D_1 + 14504 * D_2$$

Now,

Mass of the field-testing unit is 1487 kg

Acceleration due to gravity = 9.8 m/s^2

Hence Weight of the unit = m*g =1487 * 9.8 = 14572 N

EQA4.1 becomes

$$\boldsymbol{R_A + 2R_W = 14572\ [N]\ Equation - A4.1}$$

The values of D1, D2, D3 and D4 from the dimensions of the machine are as follows: -

D_1 = 1.05 m

D_2 = 4.83 m

D_3 = 0.91 m

D_4 = 7.3 m

Hence the reaction forces calculated from the above three equations are: -

R_A = 4987.218 [N]

R_B = 791.94 [N]

R_W = R_C = R_D = 4758.4 [N]

Appendix Chapter 5

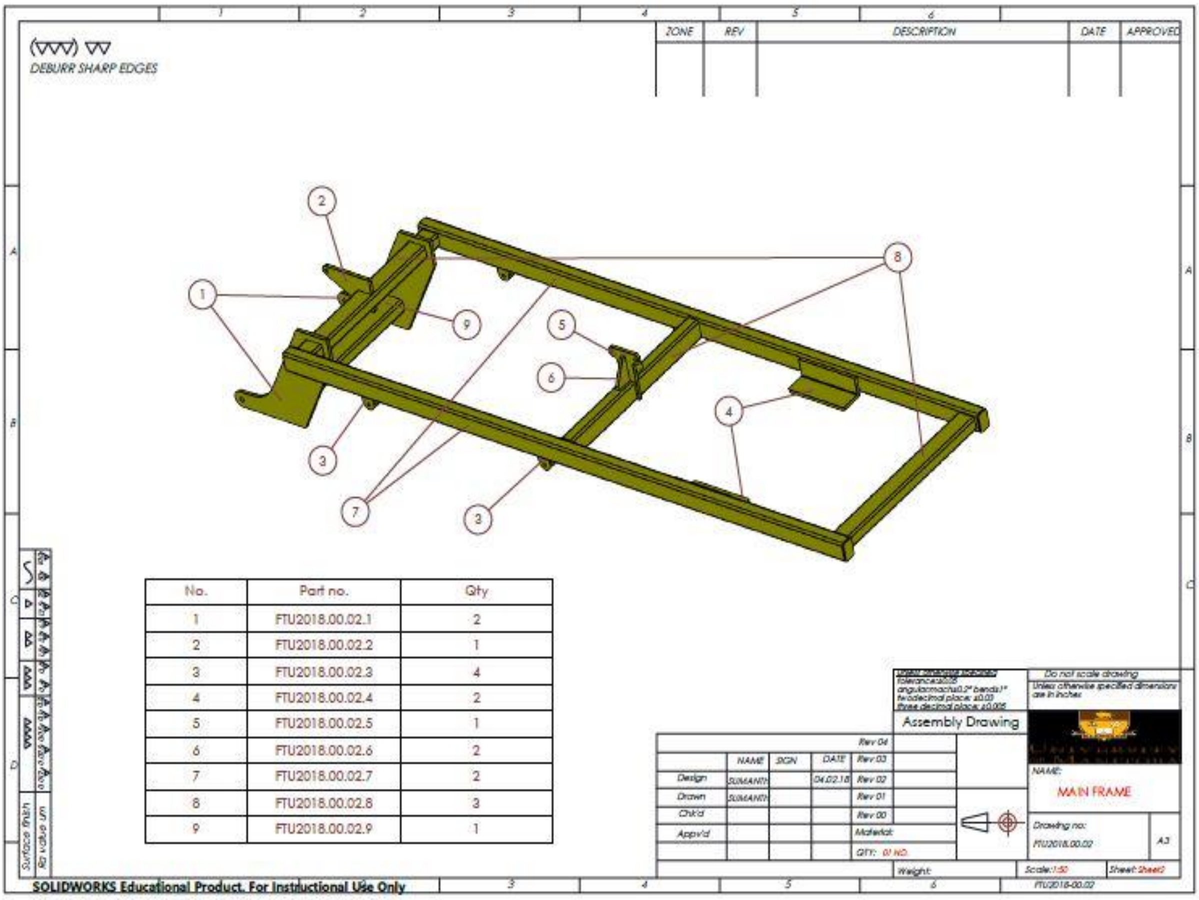


Figure A5. 1 CAD drawing showing the mainframe and its sub components

Figure A5. 1 CAD drawing showing the mainframe and its sub components

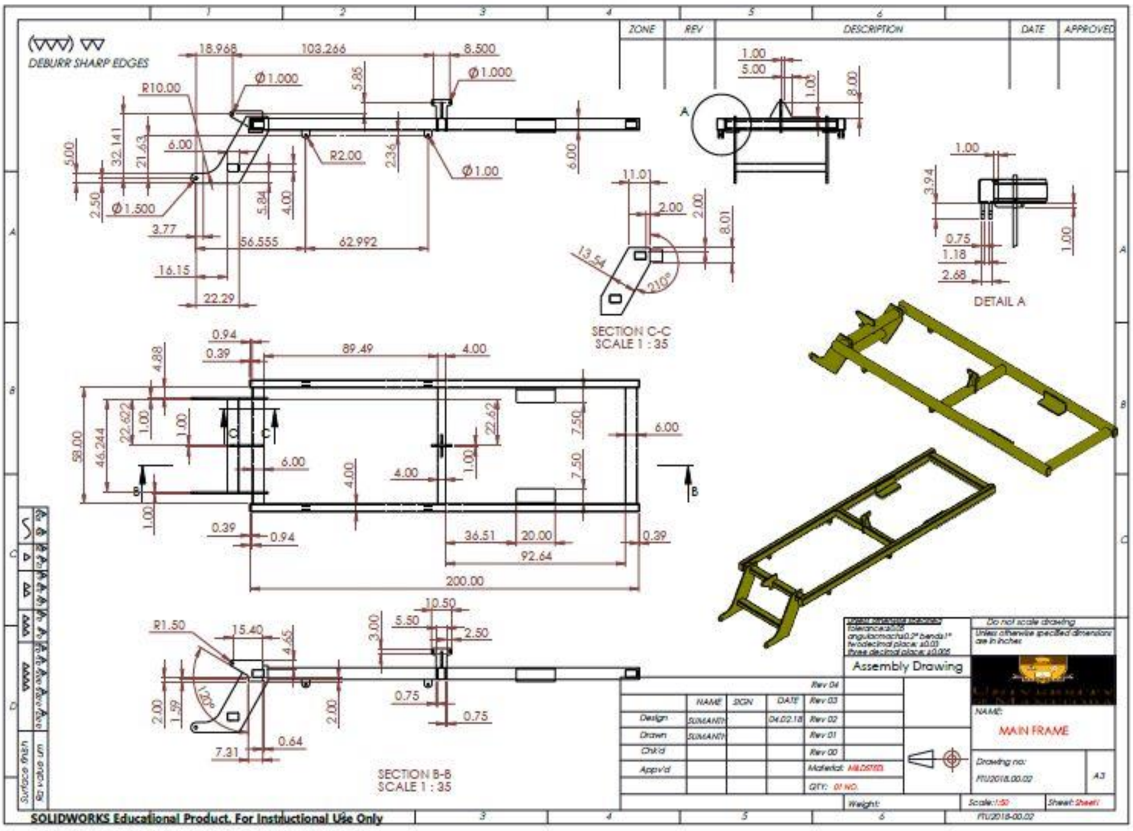


Figure A5. 2 CAD drawing showing dimensions of mainframe

Figure A5. 2 CAD drawing showing dimensions of mainframe

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Plot number
1	0.5	1	2	1.5	1.5	2	0.5	2	0.5	1	1.5	2	1	0.5	2	1	1.5	1.5	0.5	Set depth

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Travel direction

Figure A5. 3 plot numbers and operating depths assigned to 20 plots of the field.

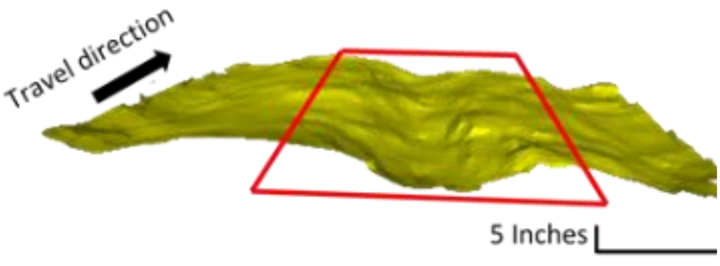
1 0.5 1 2 1.5 1.5 2 0.5 2 0.5 1 1.5 2 1 0.5 2 1 1.5 1.5 0.5

Laser scanning of the soil profile

The scanning surface area was approximately 600 by 400 mm, which covered about three furrows in the direction of width. An image was taken for each plot. Generally speaking, the scanned images had distinguishable opener furrows. A typical scan image includes a complete furrow in the middle and part of its two adjacent furrows on the sides as shown in Figure A5.4. The complete furrow of each image was cropped and plotted in Figure A5.5 to qualitatively assess the furrow profile. The furrow was larger and deeper as the working depth increased, which agreed with the measured seeding depths. With additional scans (e.g., soil surface before and immediately after the tool passage) and further image analyses, the following seeding-related characteristics could be obtained.

- Soil surface roughness
- Furrow profile
- Soil coverage and its distribution
- Soil disturbance and stepping
- Soil loosening and swelling

(a)



(b)

Figure A5.4 Furrow profile measurement demonstration (a) and an example image showing a complete furrow in the red box (b).

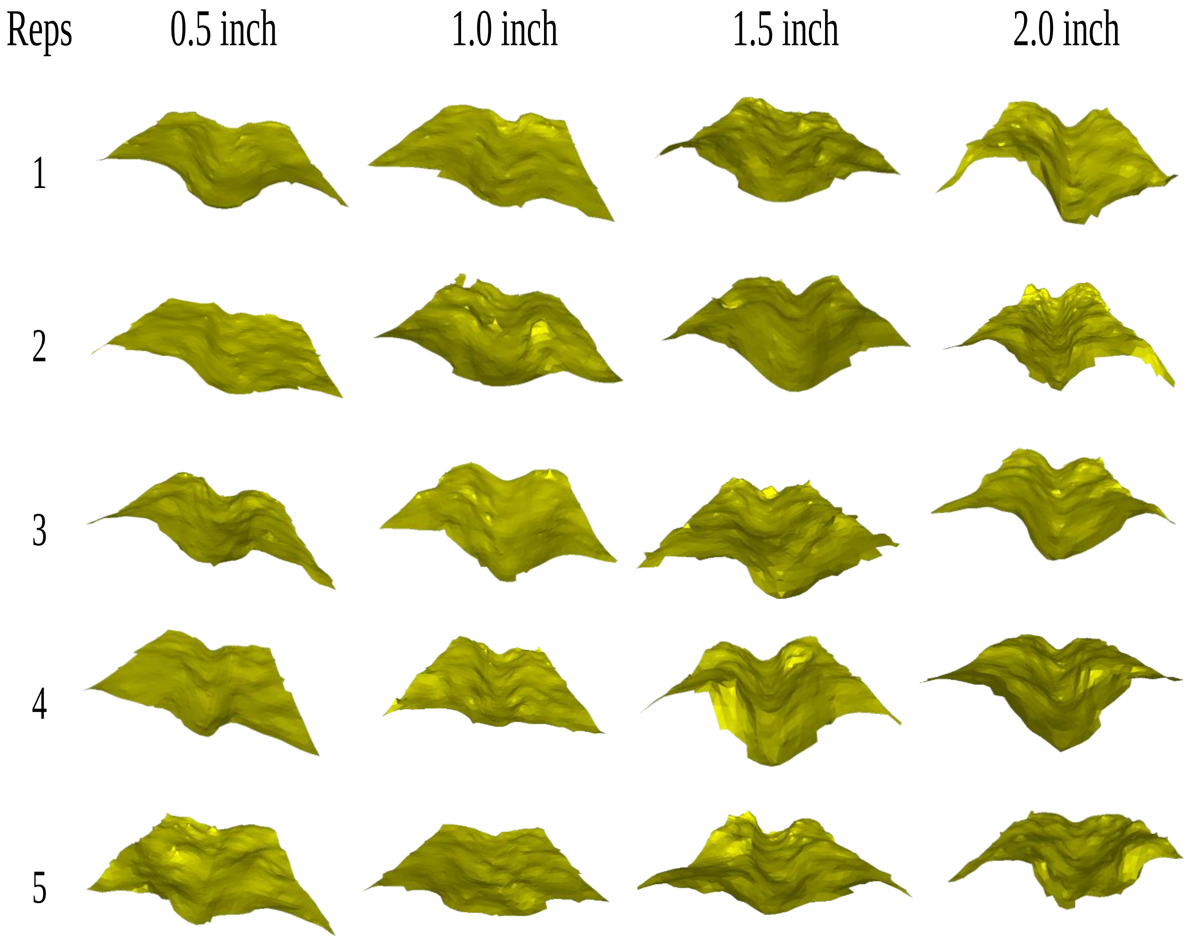


Figure A5.5 Furrow profiles of different working depths.

Table A5.1 Periodic maintenance / inspection table for the field-testing unit

Item No.	Item	Inspection Required	Each trip/test	3 Mo. / 5000 kms	12 Mo. /12,000 kms	Replacement parts
1	Tires	Check tire pressure and tread wear	✓			Tires
2	Rear lights	Check for proper light functions	✓			Rear signal lights
3	Lug nuts (wheel bolts)	Tighten to specified torque value		✓		Lug nut and bolt
4	Wheels	Check for cracks or dents			✓	wheels
5	Hub and drum assemblies	Check for scoring or wear			✓	Hubs and drums
6	Hydraulic cylinders and hoses	Check for damages or leaks	✓			Hydraulic cylinder/hose fitting
7	Toolbar frame	Check for cracks or bends	✓			Replace frame/welding
8	Gang bolts	Check for wear or cracks	✓			Grade 8 bolts
9	Subframe links	Check for cracks	✓			1-inch custom link

Table A3.2 comparison of commercial machines and their features

Model	Working depth	Working speed	Tools	Working condition	Features
John Deer VT17 series	3.5 in	5 – 10km/h	Discs, roller	Light/medium	• Pin clip system for height adjustment. • Pull type hitch. • Adjustable gang angle.
Versatile TD600N	2.5 – 5 in	Up to 19km/h	Disc, roller	Light/medium/heavy	• Hydraulic lift system • Adjustable gang angle • Floating pull type hitch
Field king FKEHDHH-26	2 – 3 in	Up to 8 km/h	Disc, roller	Light/medium/heavy	• Fixed gang angle • Manual height adjustment