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Original Research

Design and 3D-Modeling of a Solar-Powered Hydraulic Scissor Lift Table for University's Cafeterias: Advancing Sustainability and Efficiency in Food Service Operations

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Abstract

In this era of increased sustainability and efficiency, there is an increased need for solutions to reduce the environmental impact while increasing transportation in food service operations in higher education. Traditional manual food service techniques are labour-intensive and time-consuming and raise the risk of worker fatigue, minimising food service at peak hours. Disruptions caused by interruptions or personnel turnover contribute to greater operating costs through increased additional expenses and wasted resources. This study aims to overcome these concerns by creating a solar-powered hydraulic scissor lift table designed specifically for the university's cafeteria. The methodology involves conceptualising design ideas, analysing requirements, selecting components, creating 3D models, and evaluating performance using finite element simulation for structural integrity and load-bearing capacity. The results of the study confirm the platform's structural integrity with a safe load capacity of 9.81 kN, below its buckling limit. The hydraulic cylinder design is also safe, exerting a force of 8.04 kN below its buckling load of 304.34 kN. Material stress is well below the yield strength of the material (AISI 1020) and minimal deformation under loading conditions. Therefore, the study demonstrates the platform's robust structural integrity and capability of safely handling loads below its yield strength.

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INTRODUCTION

Nowadays, sustainability is crucial in all institutions, particularly those with a high environmental impact, especially concerning food transportation in higher education in Ethiopia. Implementing a solar-powered hydraulic scissor lift table in the university cafeteria is a proactive move toward sustainability and efficiency. Using renewable energy reduces reliance on fossil fuels, lowering carbon emissions and expenses. Safety and reliability are prioritised, emphasising the benefits they provide for a secure food supply regardless of climatic conditions (summer or winter). Aside from its practical benefits, it also serves as an educational tool, demonstrating the university's dedication to environmental preservation and innovation. The researchers (Liu & Sun, 2009) developed a computational model for optimising a scissor-lifting mechanism designed for high-altitude automobiles. The modified design exhibited improvements in component thickness, which improved the overall design parameters. The authors (Tian & Zhang, 2011) used Pro/E software to design an eight-meter hydraulic lift platform with dimensions of 1800 × 900 mm². They performed force analysis, optimised motion parameters, and effectively simulated its operation, resulting in smooth performance at different altitudes. The investigators (Ismael et al., 2019) used quantitative design analysis to improve the efficiency of an electric scissor lift system, utilising previously efficient component development and obtaining acceptable results than previously existing designs. (Shi et al., 2020) employed a neural network-based technique to determine the reliability of a scissor lift mechanism under heavy loads. They attained a maximum relative error of 2.1% and a minimum of 0.9%, demonstrating the viability of neural networks for reliability evaluation and presenting innovative assessment methodologies for scissor lift systems. (Jack et al., 2021) modified the mobile scissor lifting system for windy conditions in Minna, Nigeria, by addressing the lack of a support arm. Their technological modification included an ultrasonic sensor for properly measured distance.

The experimental findings demonstrated the system's stability and height accuracy, even in non-rushing wind circumstances, emphasizing the usefulness of the improved design. The researchers (Paramasivam et al., 2021) investigated the design of a hydraulic scissor lift for integrated industrial facilities in Ethiopia, focusing on actuator forces, component design, and overall functionality. The results demonstrated that the calculations offered critical data for the lift's design and analysis. In their study, (Giridharan et al., 2021) observed that stress and strain on a stainless steel scissor lifting table in a warehouse increased linearly with human weight, as determined by software modeling. The authors (Choe et al., 2022) proposed a method for improving the stability of a scissor-lifting mechanism by enhancing the support of the worktable at its highest point. Using the ABAQUS Finite Element Analysis software, they discovered that adding a hydraulic cylinder reduced worktable deformation by 94.4%, considerably increasing stability. The researchers (Xu et al., 2023) designed a self-propelled double-scissor sugarcane transporter for hilly locations, reducing the unloading angle from 120° to 30.02°, indicating increased efficiency and stability. The author (Ugwuoke, 2023) modelled a scissor elevator platform (SEP) with a load capacity of 120 kg utilising a rack and pinion gear powered by a DC motor. The SEP's design and stress analysis were simulated using CAD software, yielding a maximum stress of 1.702 MPa at maximum platform elevation and 4.928 MPa at minimum elevation.

The greatest actuation force required was 4126.980 N, with a power consumption of 26.963 W. The researchers (Kart et al., 2023) developed an advanced scissor lift platform with hydraulic assistance and automatic steering for loads up to 6 tons. A finite element study verified its structural integrity and proved safe operation without plastic deformation. (Dang et al., 2023) created and simulated a 2D model with modelling software to analyse the proposed approach for scissor lift design, particularly for double-stage structures. The simulation results demonstrated the method's accuracy and reliability in computing system reactions, highlighting its practical utility. Furthermore, (Pappalardo et al., 2024) developed and carried out an adaptive lifting mechanism to help human workers handle heavy materials more efficiently. They used computer simulations to confirm the effectiveness of their control method, highlighting the mechanism's potential for industrial applications.

The lack of solar-powered hydraulic food transportation technology at Ethiopia's higher education institutions causes considerable challenges. Without it, food transportation would be inefficient, perhaps causing delays in serving students and increasing the need for manual labor. Despite several research studies addressing CAD modelling and experimental applications, there are limited studies that incorporate renewable energy, specifically utilising a solar-powered hydraulic scissor lift table for lifting loads. The 3D modelling simulations are critical for studying the mechanical properties of parts (Efa, 2024b), by providing visualisation, stress analysis, and predictive capabilities (Efa et al., 2023; Efa, 2024c). As a result, the primary goal of this research is to fill this gap by designing and employing a 3D modelling approach for a solar-powered hydraulic scissor lift, intended for use in the university's cafeteria, with a specific focus on food transportation.

MATERIALS AND METHODS

Steel has been preferred over iron because of its higher strength and fracture resistance, making it better suited for structural needs (Giridharan et al., 2021). Steel is also essential due to its strength and durability of lifting devices (Costa et al., 2023). Steel's excellent tensile strength and capacity to withstand enormous loads make it ideal for mechanically demanding applications (Dang et al., 2023). The author (Ganesan, 2017) emphasizes the importance of steel mechanical qualities such as strength, stiffness, and durability, especially in providing the safety and efficiency of scissor lift operations. Furthermore, (Ismail et al., 2013) highlighted steel's unique features, such as opacity, glow, less weight, ease of production, great mechanical strength, and high thermal and electrical conductivity, which enable its applicability for scissor lift applications. However, high-carbon steel is prone to stress and deformation concerns in scissor lifts, exceeding the allowed stress of carbon steel and needing material modification (Choe et al., 2022). AISI 1020 low carbon steel has been selected in this study for hydraulic scissor lifts table due to its strength, weldability, corrosion resistance, low weight, and machinability (Civi & Iren, 2021; Fernandez et al., 1998). Additionally, its superior machinability enables the development of complex hydraulic components and system designs in CAD software (Patil, 2024; Dengiz et al., 2018). These properties facilitate easy fabrication while maintaining structural integrity.

The material properties for AISI 1020 are shown in Table 1, which is sourced from the SolidWorks Material Library. These properties have been further validated through laboratory testing from existing literature, and the results align with those provided in the software's material library, as confirmed by (Dengiz et al., 2018; Shao et al., 2013). A lithium-ion battery, 150W monocrystalline solar panels, an MPPT (Maximum Power Point Tracking) charge controller, a pure sine wave inverter, and a reduction motor-powered hydraulic pump were used in this investigation.

Table 1

Material properties of AISI 1020

Material Properties	Value and Units
Mass Density	7800 kg/m^3
Poisson's ratio	0.30 (no unit)
Tensile Strength	4.2×10^8 N/m^2
Shear Modulus	7.7×10^{10} N/m^2
Elastic Modulus	2×10^{11} N/m^2
Yield Strength	3.5×10^8 N/m^2

A research methodology for creating a solar-powered hydraulic scissor lift table begins with design conceptualisation, which involves brainstorming and iterative design explorations to generate and refine concepts into a viable design. This is followed by a detailed requirements analysis for the lift table, which takes into account parameters such as load capacity, lifting height, and power source preferences. These design specifications are then used to choose appropriate hydraulic and solar power components. After selecting the components, Solid Works® 2020 software is used to build extensive 3D models and assemblies for the scissor lift table. The design is virtually tested and evaluated using simulation software, and Finite Element Analysis (FEA) is used to assess structural integrity, stress distribution, and dynamic behaviour under various loading conditions as the overall process is shown in Figure 1.

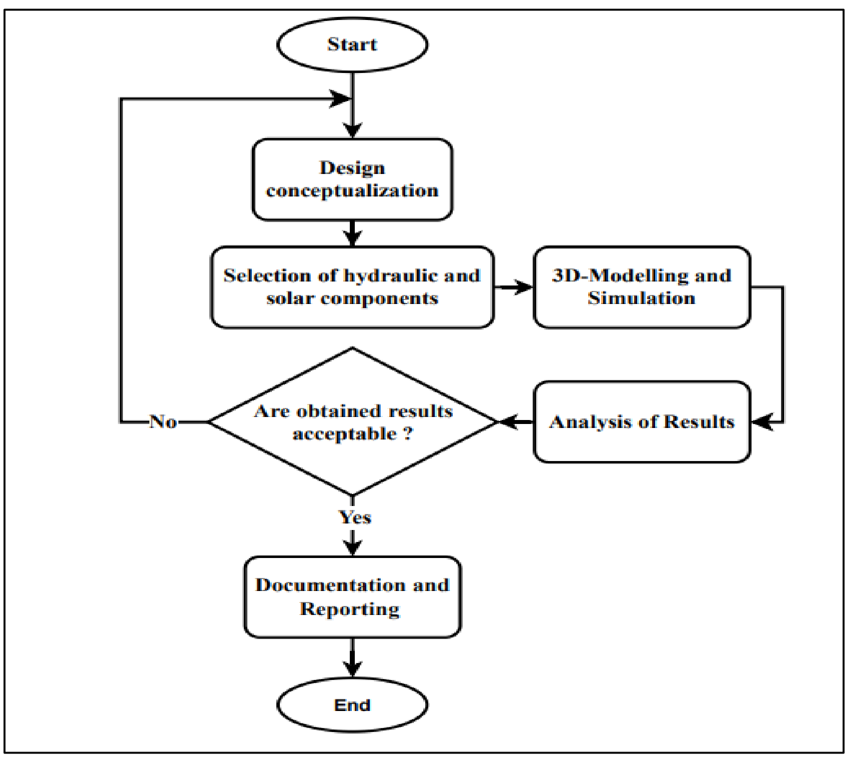

Figure 1. *The overall Research Methodology*

RESULTS AND DISCUSSION

Designing of scissor lift components

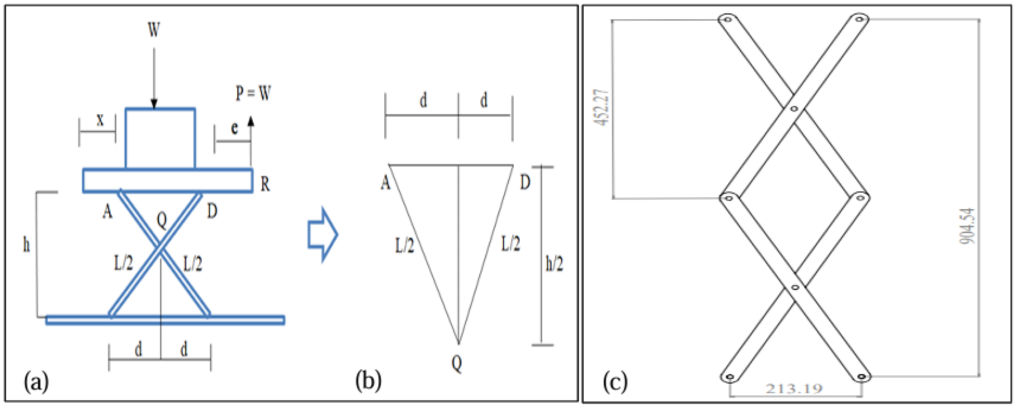

Figure 2 (a-c). *The FBD of the scissor lift*

Based on the free body diagram from Figure 2 (a) and (b), the Pythagorean Theorem can be applied as:

$$d = \sqrt{\frac{l^2 - h^2}{4}}$$

Where the total height (h) of the scissor lift is 1.8 m, it is scaled down to 1:2, resulting in a height of 904.4 mm. Therefore, the height of a single scissor becomes 452.27 mm, 2d = 213.19 mm, L = 452.27 mm. For better balance and stability, assuming as:

$$x = e = \frac{L - 2d}{2} = 119.54\ mm$$

Therefore, based on the obtained data and assumed parameters, the scissor legs have been designed as illustrated in Figure 2 (c). The 3D-modelled scissor linkages shown in Figure 3 (a) visually represent the designed results.

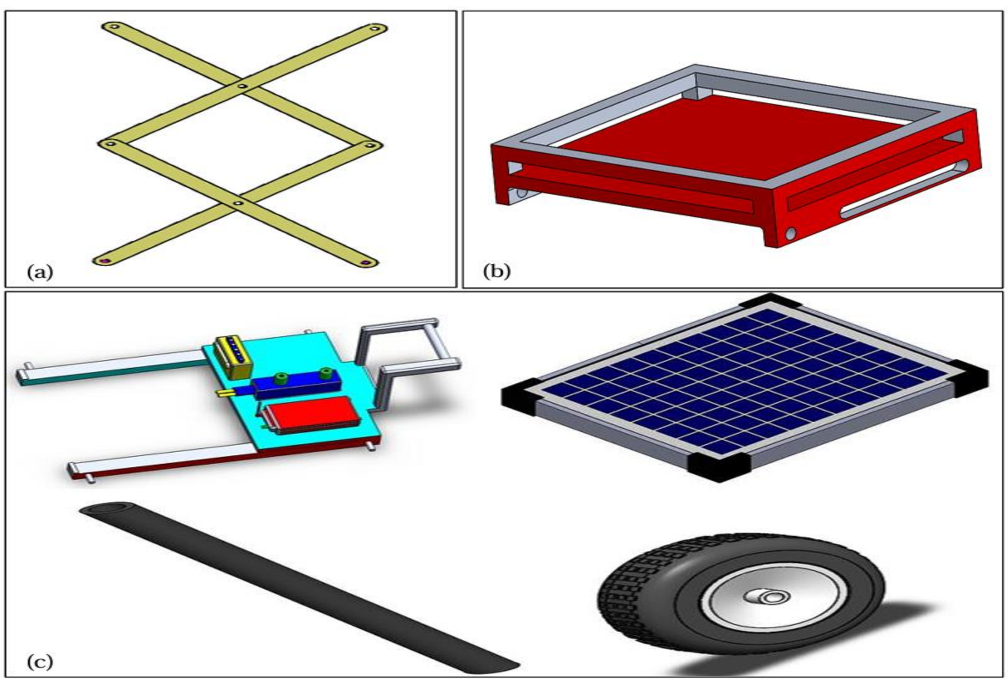

Figure 3 (a-c). *3D-Modeled Components*

Upper and Lower Platform Design Analysis

The upper and lower platforms can be determined by considering dimensions that suit the overall assembly of the components, space constraints, required load capacity, and material availability. Therefore, in this study, with a length of 1320 mm scaled down to 1:2, it becomes 660 mm, a width of 1200 mm scaled similarly to 600 mm, and a thickness of 50 mm scaled to 25 mm. With a density of steel (ρ_{mat}) at 7900 kg/m^3, a permissible mass of 1000 kg, a scissor angle of 45 degrees, and gravity at 9.81 m/s^2, the weight of the upper platform is calculated as follows:

$$V_{UP} = LWT = 600 \times 600 \times 25 = 9.9 \times 10^6 mm^3$$
$$V_{UPF} = (600 \times 50 \times 2) + (600 \times 50 \times 2) = 1.26 \times 10^5 mm^3$$
$$V_{UPT} = 9.9 \times 10^6\ mm^3 + 1.26\times 10^5\ mm^3 = 1.0026\times 10^7 mm^3$$
$$M_{UP} = \rho_{mat} \times V = 7900\ kg/m^3 \times 1.0026\times 10^7 \times 10^{-9}\ m^3 = 79.2\ kg$$
$$W_P = M_{UP} \times gravity = 79.2\ kg \times 9.81\ m/s^2 = 777\ N$$
$$P_{all} = M_{all} \times gravity = 1000\ kg \times 9.81\ m/s^2 = 9.81 kN$$

Where, V_{UP} represents the volume of the upper platform plate, L is the length, T is the thickness, W is the width of the platform, V_{UPF} is the frame volume of the upper platform, V_{UPT} is the upper platform's total volume, M_{UP} is a mass of the upper platform, W_P is the weight of the platform, P_{all} is an allowable load and M_{all} is permissible mass

Therefore, based on the assumed and designed values, the platform has been modeled as shown in Figure 3 (b). This model incorporates design ideas and specifications to precisely represent the dimensions and assembly relationships of the scissor lift system. It serves as an extensive representation, providing details on the physical components and their interactions within the assembly. After precisely designing the scissor legs, hydraulic cylinder, and platform, the remaining parts are modelled to precisely fit the dimensions of the designed components, as displayed in Figure 3 (c).

Hydraulic Cylinder Design Analysis

In this study, the hydraulic cylinder was designed with a bore diameter of 40 mm and a length of 400 mm. The load applied to the upper platform directly influences the hydraulic cylinder, which can be determined as the scissor arm force using the following formula:

$$F_{hc} = \frac{\left(W_p + \frac{P_{all}}{2}\right)}{Sin\ 45^o} = \frac{\left(777\ N + \frac{9810}{2}\right)}{Sin\ 45^o} = 8.04\ kN$$

Where, F_{hc} is the force applied to the hydraulic cylinder.

Hence, the overall force applied on the hydraulic cylinder is 8040 N, which represents the combined effect of the weight placed on the upper platform and carried via the scissor mechanism.

The buckling analysis of the hydraulic cylinder

The buckling study of a hydraulic cylinder entails determining its structural integrity under compressive loads. It assesses the cylinder's ability to withstand buckling, a failure mechanism characterised by lateral displacement due to excessive axial compression. As a result, the hydraulic cylinder's buckling analysis has been conducted using the equation shown below.

$$P_B = \frac{EI\pi^2}{L^2}$$
$$I = \frac{\pi d^4}{64} = \frac{\pi \times (0.04)^4}{64} = 1.26 \times 10^{-7} m^4$$
$$P_B = \frac{2\times 10^{11} \times 1.26 \times 10^{-7} \times \pi^2}{(0.904)^2} = 304.34\ kN$$

Where is P_B represents the buckling load, d is the diameter of the cylinder (taken as 40 mm), L is the length of the cylinder (taken as

904.54 mm), E_{st} is Young's Modulus of AISI 1020 steel (2×10^{11} N/m^2)

Since the overall force (8.04kN) is lower than the obtained buckling load (304.34 kN), the intended hydraulic cylinder is considered safe for operation. This emphasizes the significance of conducting extensive structural design to ensure hydraulic system reliability.

Modeling, meshing and Finite Element Analysis (FEA) of scissor lift linkage

It is extremely important to model the scissor leg or linkage shown in Figure 4 (a) for meshing and Finite Element Analysis (FEA) in a scissor lift. These components carry heavy weights, which is crucial for safety and reliability. FEA is used for assessing load-bearing capacity, structural integrity, and performance (Efa, 2024c; Efa, 2024a). Designers can readily discover weak places and optimize designs for safety through analysis of stress, displacement, and strain data. This rigorous examination confirms that scissor lifts conform to operational requirements and safety standards, thereby enhancing performance and reliability.

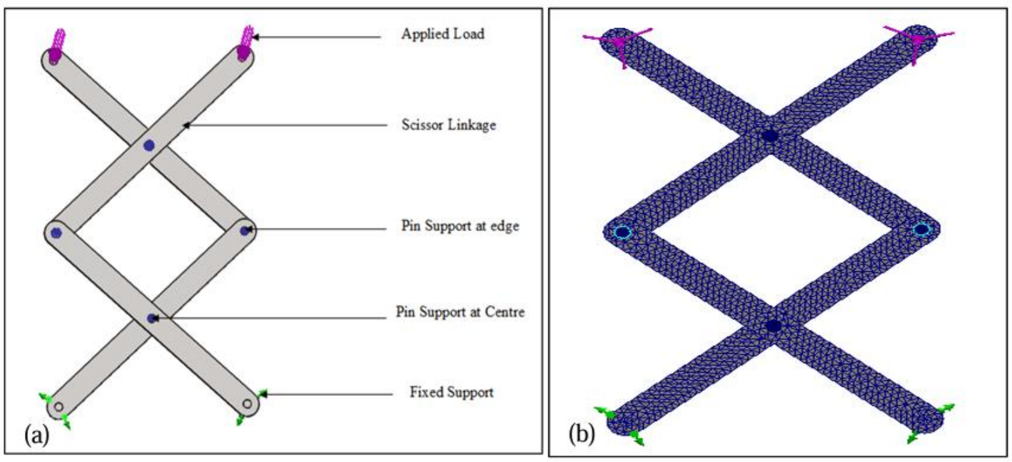

Figure 4. *Modeling and Meshing of Scissor Lift Linkage*

As a higher load is imparted to the scissor leg, it has been chosen for reliability testing using Finite Element Analysis (FEA). The meshing process utilized a solid mesh type with standard meshing, such as 16 Jacobian points for high-quality meshing, an element size of 6.28mm, and a meshing tolerance of 0.31mm. This resulted in a total of 16,252 nodes and 7,450 elements, as the meshed result is shown in Figure 4 (b).

Results of Stress, Strain and Displacement

The Finite Element Analysis (FEA) of the scissor lift linkage or leg, using AISI 1020 material, provides significant details on its structural performance under various loading conditions. The maximum equivalent stress identified throughout the analysis is 1.07×10^7 Pa, as illustrated in Figure 5 (a) and (b) showcasing both the maximum stressed area and the simulated results respectively. As soon as the result is compared to the yield strength of AISI 1020 steel, which is 3.51×10^8 Pa, it becomes evident that the stress level is significantly lower than the material's yield strength.

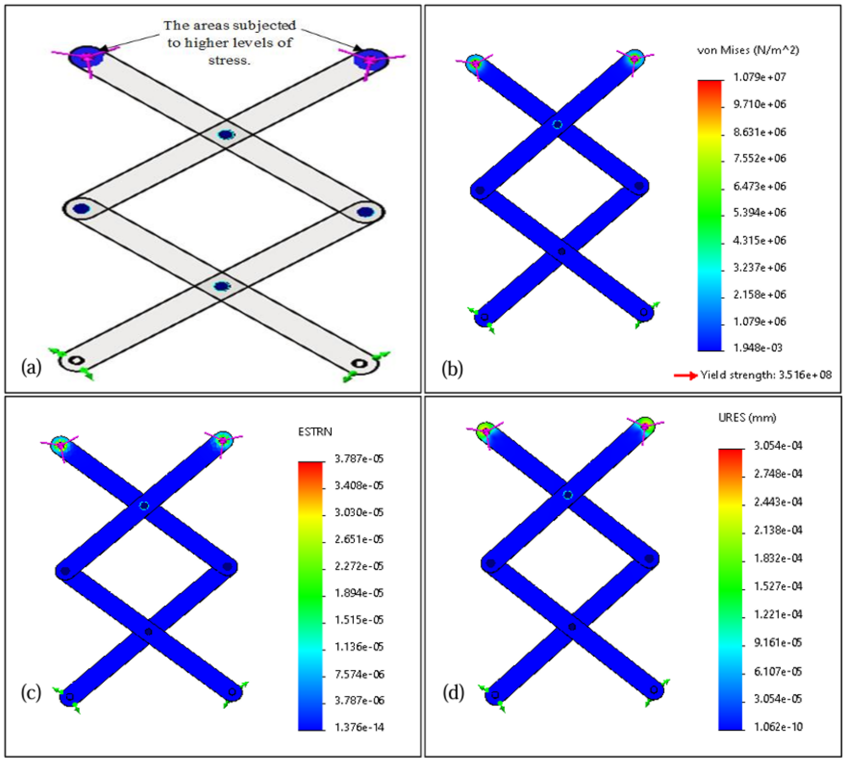

Figure 5 (a-d). *Simulated Results of Scissor Lift Linkages*

As a result, the imposed load cannot be expected to cause plastic deformation or failure of the material. Additionally, as demonstrated in Figure 5 (c) the equivalent strain obtained from the analysis is $3.8 \times 10^{-5}\ mm/mm$, indicating the total strain developed by the material. This value represents the deformation in the material caused by the applied load. Given the low strain value, it implies the material's deformation is relatively small and indicates no major risk of failure. Furthermore, as indicated in Figure 5 (d) the resultant displacement of the scissor lift linkage under the specified load conditions is determined as $3.054 \times 10^{-4} mm$. This displacement encompasses both rigid body movements and material deformations. Therefore, the displacement value remains within the acceptable range, showing that the scissor lift's functionality and safety have not been influenced by the applied load. In general, the FEA results confirm the structural integrity and reliability of the scissor lift linkage designed of AISI 1020 material. With stress levels considerably lower than yield strength, minimal equivalent strain, and acceptable displacement values, the scissor lift can safely bear operational loads. These results emphasize the need for extensive investigation to provide the safety and performance of mechanical components in design and manufacturing environments.

Assembly and working principle

To elucidate the working principle of this study, Figure 6 illustrates the assembled hydraulic scissor lift along with its nomenclature. The battery, recharged via solar panels or hydroelectric power, provides energy. Solar panels capture sunlight, generating DC energy, which is regulated by a charge controller before being stored in the battery. This stored DC energy can power DC or AC appliances, with DC converted to AC by an inverter to operate an asynchronous motor, determining the lift's capacity and speed. The solar panel is mounted on the roof to collect sunlight. The generated DC power is transmitted to the charge regulator, which is in charge of controlling the charge flow to protect the battery from overcharging. The DC charge is then stored in the battery. However, the stored DC charge cannot directly power the motor pump. Instead, it must be converted to AC charge by the inverter, which then pressurizes the hydraulic oil to lift the weight. A hydraulic lift table operates by raising and lowering through the forced movement of hydraulic fluid into or out of hydraulic cylinders. As hydraulic fluid is injected into the cylinder, it extends, pushing the scissor legs apart, thereby raising the platform vertically. The lift table is supported during elevation by a column of fluid, maintained within the cylinders by a check valve. Conversely, the lift table descends through a solenoid-operated down valve, controlling the fluid's release from the cylinder. This valve, typically normally closed, prevents descent during power loss. The flow control (FC) valve regulates descent speed, maintaining a consistent flow regardless of load.

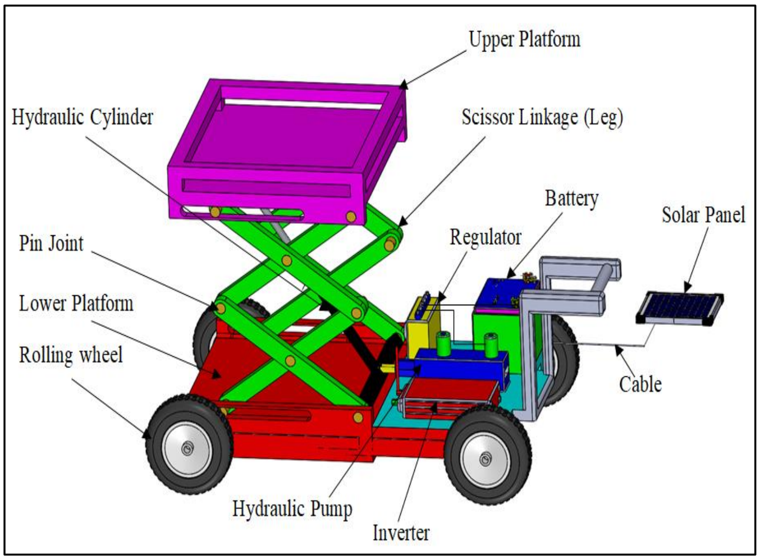

Figure 6. *The Assembled Scissor Lift with its Nomenclature*

CONCLUSION

The design and finite element simulation conducted on the solar-powered hydraulic scissor lift platform has yielded promising results. The designed permissible load on the platform is 9.81 kN, which is less than the material's buckling load, confirming its structural integrity and capacity for safe operation. The findings of the hydraulic cylinder design exhibit its safety, as the overall force (8.04 kN) is less than the obtained buckling load (304.34 kN). The maximum equivalent stress (1.07×10^{7} Pa) is considerably lower than the yield strength of AISI 1020 steel (3.51×10^{8} Pa), confirming the material's safety. The analysis resulted in a maximum equivalent strain of $3.787\times 10^{-5}\, mm/mm$, confirming minimal material deformation and minimum risk of failure. The displacement of the scissor lift linkage ($3.054\times 10^{-4} mm$) under specified load conditions indicates that the material compensates for both rigid body movements and material deformation. Therefore, the simulated stress, strain, and displacement values remain within acceptable ranges, indicating that the scissor lift works effectively and safely.

Credit authorship contribution statement:

Dejene Alemayehu Ifa: Project administration, Resources, Methodology, Investigation, Formal analysis, Data curation & Conceptualization.

Dame Alemayehu Efa: Writing – review & editing, Validation & Supervision, Software, Visualization & Writing – original draft.

Declaration of competing interest

The authors declare that they have no conflicts of interest.

Data availability statement

All data are availablefrom the corresponding author upon request.

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