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DESIGN OPTIMIZATION OF STAIR CLIMBING CART FOR DEVELOPING COUNTRIES

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Abstract: Most of the people living in developing or less developed countries have limited earning to provide somehow their basic needs & usual staff. Carrying goods is a regular task in life & several products have been invented to minimize efforts in this purpose. But the product's price & features are not optimum for the people of fewer earnings. Stair climbing cart is very useful for those houses where a lift is not available and goods have to be carried frequently upstairs. In this research, the mechanical design has been modified so that the manufacturing cost can be minimized. Finite element analysis has been performed upon the design to find out how the manufacturing cost can be reduced by making the design optimal for manufacturing cost and process. The result shows that the structural members should not be processed further because any tooling operation will require an extra machine as well as an extra cost. Only the wheels are possible to subject under optimization by reducing material as well as weight. This article will be a valuable asset for the mass manufacturers of this type of product.

KEYWORDS: Stair Climbing, Cost minimization, Innovative features, Design modification, Process.

1 Introduction

Cost is a primary factor in business that helps to compete with competitors providing customer satisfaction [1]. But if the product can not meet the customer's needs, they will not buy it at all even at the lowest price. Products are designed for a target customer group according to their buying capability, lifestyle, purpose of use, physical capability, etc. Before designing a product, existing features & price of competitors including their customers buying capability is very efficient & effective to determine a new customer group who are not served by the competitors [2]. This research represents the design of the stair climbing cart with new innovative features. The main structure on which the load would be carried has been designed with fewer materials than the existing’s. To increase the stability of the cart 4 wheels mechanism has been used. With the help of lower 2 wheels which will be in touch with the ground, the cart with load can be balanced. This feature will reduce stress while pulling goods on stairs. A very high tensile strength is needed to carry loads on stairs. The reduced weight of the design will significantly reduce the tensile stress during pulling upward the cart. Also, compressive stress will be reduced during pulling downward. A better gripping system has been provided considering ergonomically factors of the customers. The tensile-compressive stress when pulling & gripping are two major human factors in the design of this stair climbing cart [3-7]. Only fewer types of joints have been used in this design so that the difficulty of manufacturing minimizes. Only welded joints increased the simplicity & sustainability of the cart.

The Bill of material and manufacturing process layout added in this research will provide the manufacturers a complete view to determining the manufacturing cost, required machines,

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number of operators required, tooling cost, overhead cost, etc. to figure out the feasibility of the mass production of this product for commercial interest. The design optimization has been verified with finite element analysis. The structural members cannot be optimized further because this will raise extra tooling costs and require extra machines which will result in an additional budget for the project and create obstacles in the project feasibility. Only the wheels are possible to topology optimization by reducing some materials following a pattern which was checked by stress distribution upon the wheel at the maximum load that can be carried by the cart safely.

2 Literature Review

A lot of Patents have been found on Stair Climbing Cart. But none considered the cost minimization or design for less earning customers. Most of the patents focused on ease of load-carrying over the stairs, mechanism, structure, wheel design, etc. Very few researches have given importance to the manufacturing cost reduction of these types of products. Some closely related works of literature are discussed below.

Cheng, C. J. (1989) patented such a stairways accessible cart where two main wheels & two auxiliary wheels were foldable and the auxiliary wheels were spring-loaded by two-way hinges [8]. Diener, H. (1985) patented a cart that includes large wheels for movement over rough terrain while the cart is loaded and a set of smaller wheels for movement of the cart within buildings. The cart also includes a stair climbing apparatus to enable pulling a loaded cart up a flight of stairs [9]. Andruchiw, R. (1978) patented a stair-climbing device using reversible electric motor & load bearing shoes pivotally connected with load-bearing shoes. The device can move forward & backward with pivotally connected arms & sensing head at the contact of the threads [10]. Carlile, E. (1989) patented a hand-propelled cart which includes a separable wheeled frame having a different collapsible section to carry different types of goods [11]. Grace, J. (1997) patented a collapsible, foldable cart, having a frame with spaced-apart first and second longitudinal frame members defining a plane, and a pair of wheels and a wheel axle connected to the frame [12]. Kazmark Jr, E. A. (1999) patented a collapsible cart that includes a pivotable platform, a pivotable handle, and collapsible and adjustable tube assemblies for placing the cart in an extended or retracted position [13]. Martin, W. B. (1987) patented a unique stair climbing cart using only two wheels. Each wheel is comprised of a plurality of lobes like teeth on a gear, each lobe has two surfaces which are symmetrical around a lobe centerline, with each surface being made up of a portion of an involute curve defined by a circle having a particular radius. The wheel may be made to specifications allowing exact fit on a particular size stairstep and a properly fitting wheel will move in a close approximation of a straight line parallel to the staircase incline as it moves up a flight of stairs [14]. Vom Braucke, H., & Vom Braucke, M. (1997) patented a collapsible hand trolley which has two wheels pivoted about a horizontal axis mounted at the lower end and folding-unfolding features also about vertical axis [15]. Hong, H. S., Seo, T., Kim, D., Kim, S., & Kim, J. (2013) designed an optimum hand-carrying rocker-bogie mechanism for stair climbing [16]. Wyrick, S. (2007) patented a cart which has three-wheel assemblies in both sides that are designed to rotate when contact is made with stairs, thereby allowing the cart to climb the stairs [17]. Zhang, L., & Xi, F. (2012) worked on the design optimization for the stair-climbing wheelchair [18]. Richard Danziger (2015) patented a stair climbing assistance device which contains a first grip and a second grip on opposite sides of the central axis and each grip being connected to the other by first and second connecting members that combine with the first and second grips to form a handle frame [19]. (Cheng, 2018) patented such a stair climber where a total of 8 small wheels has been used with ergonomically designed handles. The height can be adjusted to the product and there are two chambers for product housing [20]. (Behera & Gupta, 2018) designed a stair climbing assisting wheelchair with two degrees of freedom legs containing four-bar parallel linkage and each leg is fitted with actuators [21]. Hasan, M. Z., & Rashid, M. (2019) designed this stair climbing cart with low-cost available material considering the customer requirements and prepared a quality function deployment chart so that engineering specifications also can be understood. The design was sustainable and reliable because of fewer types of joints and high load-carrying capacity [22].

3 Methodology

The mechanical design of the stair climbing cart has been developed & modified considering available materials. Low-cost available materials help to reduce the cost of a product easily. Also, the availability of the technology of processing the materials is very important during the design of the product. Continuous material supply at the lowest cost has a great impact on product quality & cost [23-26]. The design of the cart with main parts has been illustrated in figure 1 where part no. 2 the load-carrying base is the main part of this cart. The object will be placed on it. The no. 6 part of which name is load support is added to prevent the load from slipping backward. In case of carrying heavy loads, ropes can be used to tie the loads with the load support & the frame under the handle. The dimensions of the stair climbing cart are bellowed figure-2. The mainframe of the cart is designed to make with structural members which will be joined by welding after the cutting according to the required size and edge preparation. The members are available at a cheaper price and the use of structural members will reduce the manufacturing process step and operator. Also, the structural members with a welded joint will reduce the utilization of extra machines as well as operator cost.

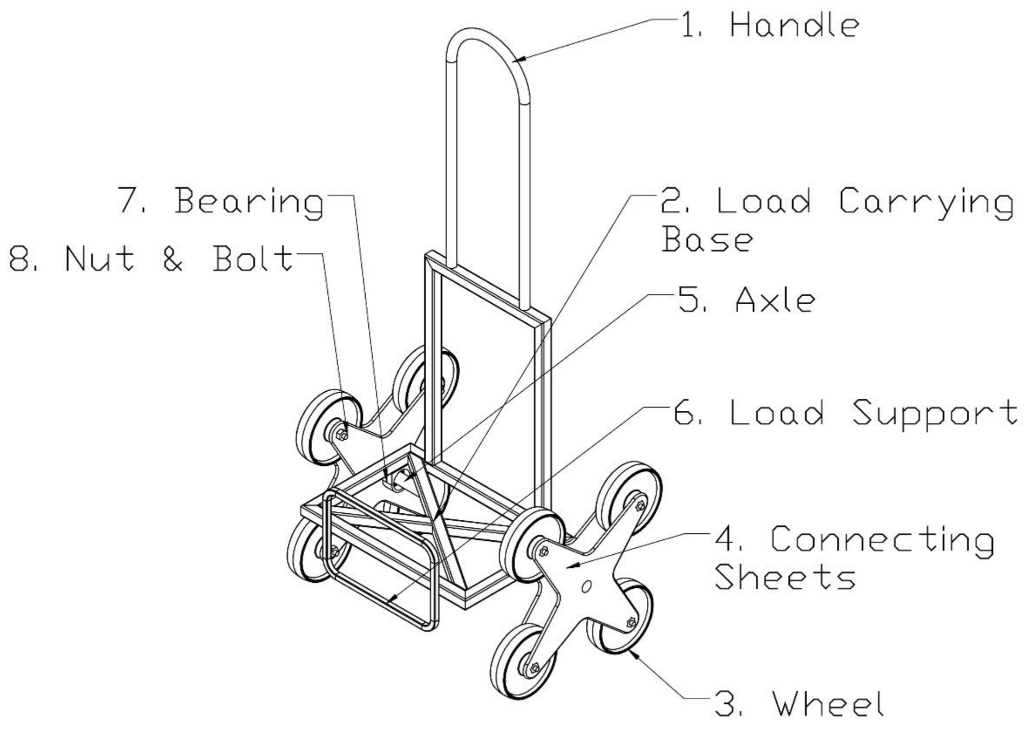

Fig. 1 Main Parts of the stair climbing cart

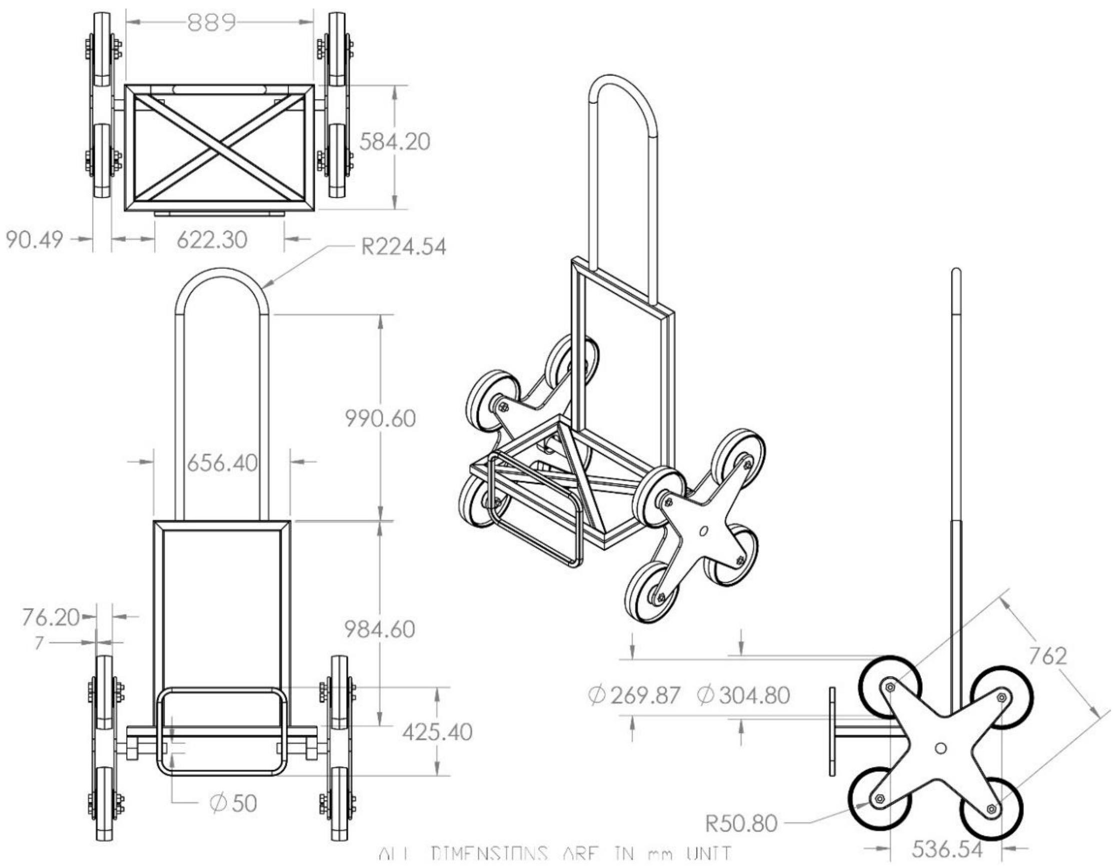

Fig. 2 Required dimensions of the stair climbing cart

The structural member sizes can be optimized by selecting the correct dimensions using the anthropometric measurement of any region for which the product will be manufactured.

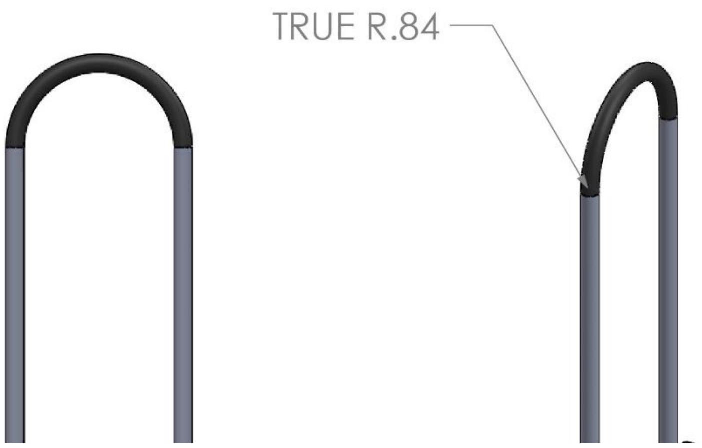

Fig. 3 Handle diameter & material

The anthropometric measurement concept for better gripping has been provided in the design of the handle. The total diameter of the handle is 1.68 inches (42.67 mm approximately) including gripping material [27]. The gripping material is soft rubber which will reduce stress in fingers during carrying the cart by holding it in the handle [28]. In the previous designs, ergonomic factors in the handle for comfort gripping has not been considered as much as this design. Many stair climbing carts have a plastic gripping system on the handle which requires extra mold and molding machine including an operator to manufacture the part. In this design, the handle making will be a very simple process. The structural member of the handle has to be bend and inserted into the rubber gripping which will be cut equal to the length of the arc after bending.

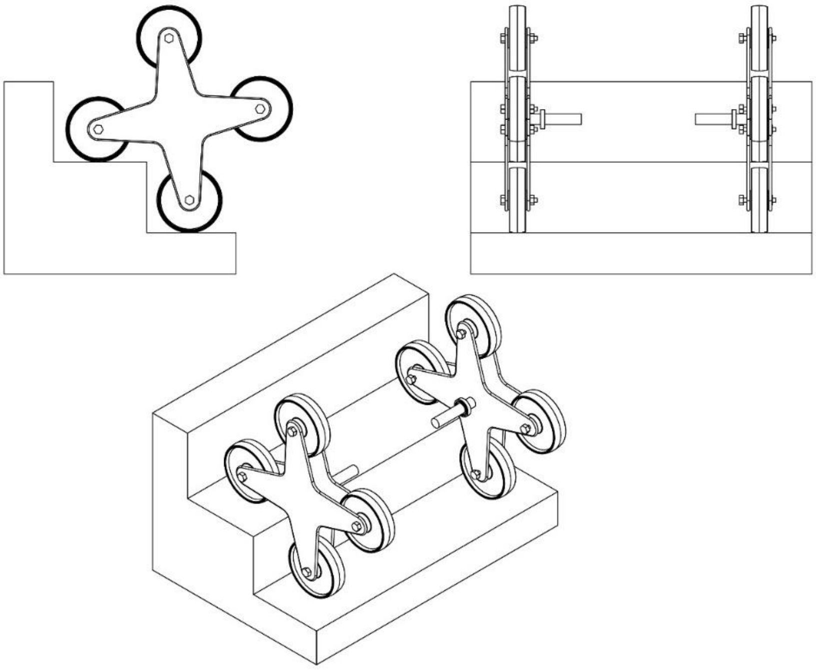

Fig. 4 Pause & rest feature while climbing stairs.

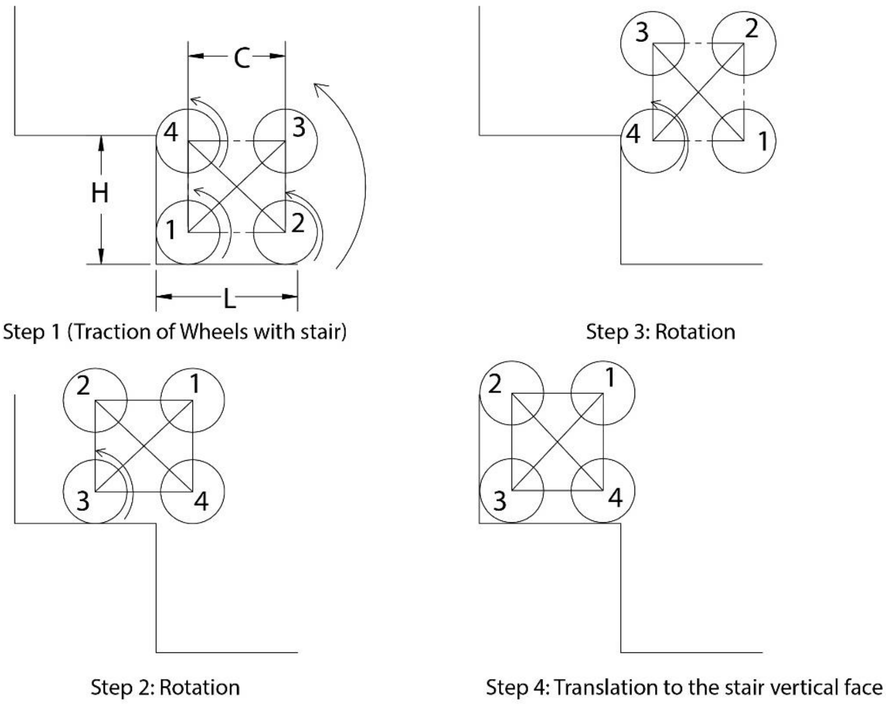

Fig. 5 Stair Climbing Mechanism with four wheels

Table 1 Bill of Material for the Stair Climbing Cart

S/L	Description of the Part	Quantity	Production Process
1	2x2 square pipes	15 ft	Local Vendor
2	1x1 square pipes	12 ft	Local Vendor
3	0.5 in pipe	8.5 ft	Local Vendor
4	5972K129_BALL BEARING	2 pieces	Local Vendor
5	Nuts	8 pieces	Local Vendors
6	Bolts	8 Pieces	Local Vendors
7	Plastic Wheels	8 Pieces	Injection Moulding
8	Soft Rubber Tube	0.5 m (1 Pc)	Local Vendors

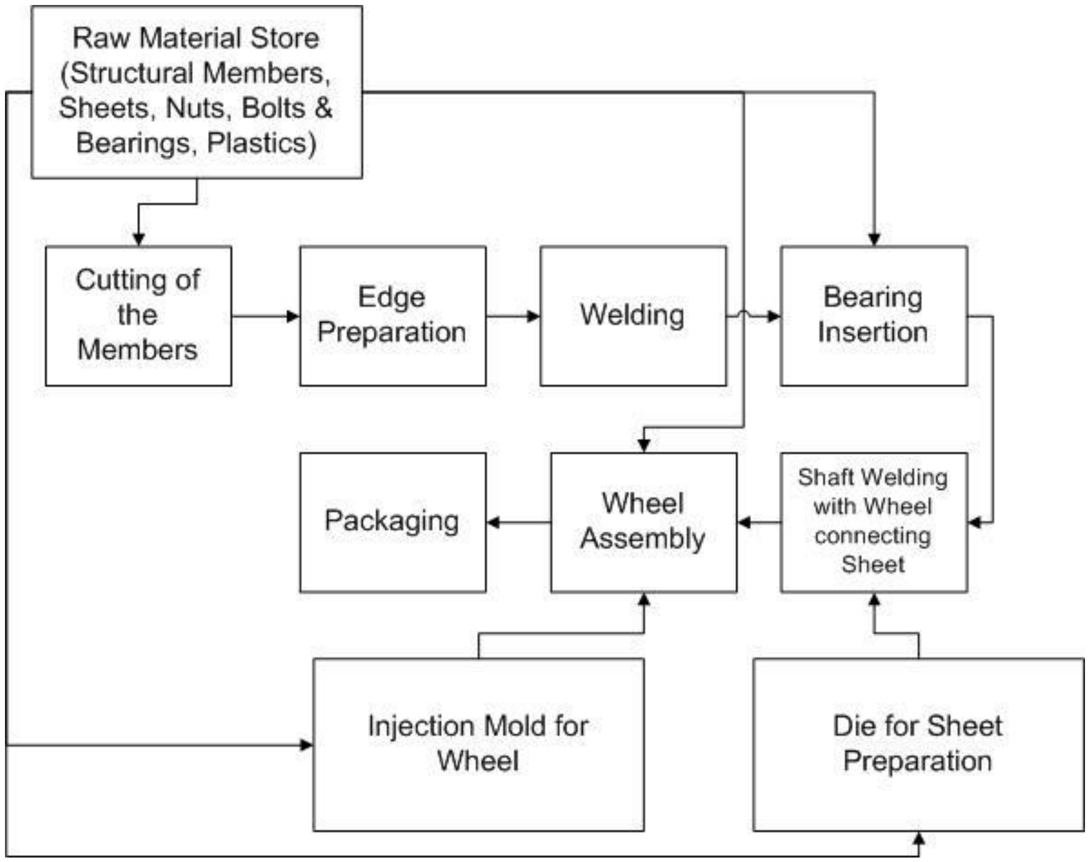

Fig. 6 Manufacturing Process for the Stair Climbing Cart

4 Result Analysis

4.1 Finite Element Analysis on the Handle

The tensile strength of the handle portion is very high. Simulation in ANSYS Workbench 17.0 was done applying different tensile loads on the handle. There is a very low probability of failure under heavy tensile load while carrying objects. Figure-6 represents the maximum shear stress simulation result when a 500 N tensile load is applied on the handle. This is a static simulation & the lower portion of the structure is fixed. Different results in stress for different loads are bellowed better understanding. The structure is highly sustainable in the tensile load. A very high magnitude of the tensile load is required for failure [28]. Usually, the tensile load will not be more than 3000 N. Heavier objects more than 30 kg are very cumbersome in size & shape just like beds, heavy furniture, etc. and these are not carried on stair climbing carts.

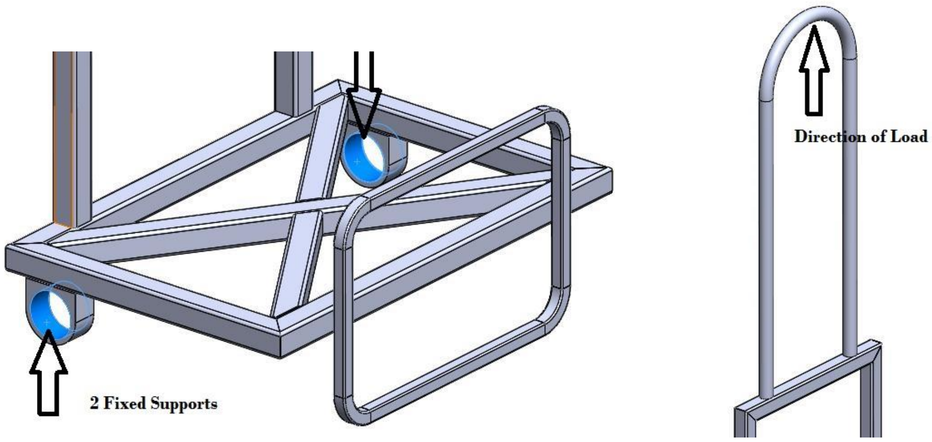

Fig. 7 Constraints and Boundary conditions with direction of loads

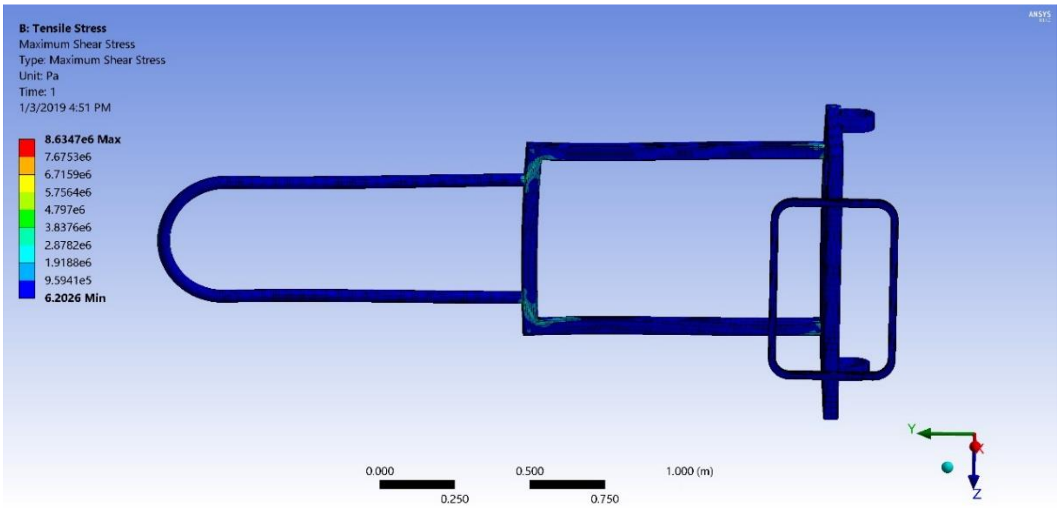

Fig. 8 Maximum shear stress under 500 N tensile load on handle

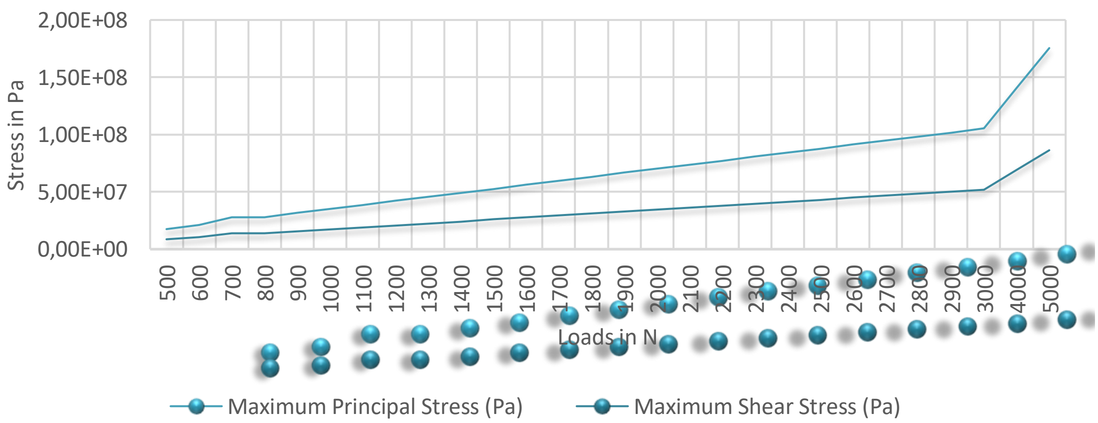

Fig. 9 Tensile Load vs Maximum principal and Maximum Shear stress plot

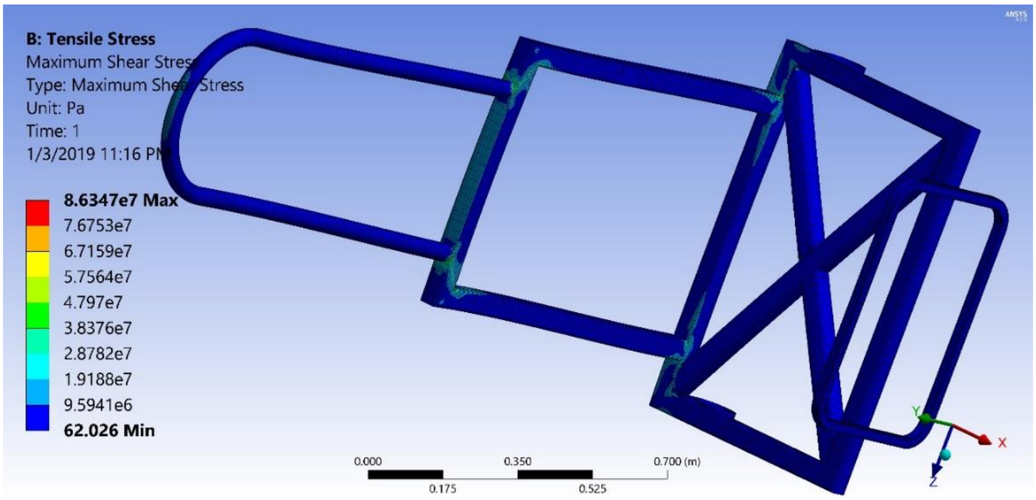

Fig. 10 Maximum Shear stress at 5000 N tensile load

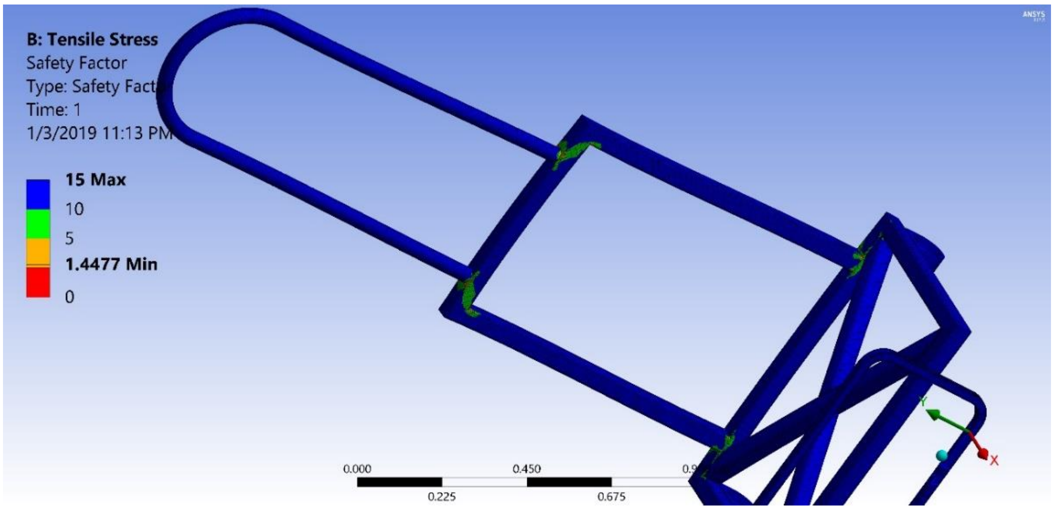

Fig. 11 Factor of safety distribution at 5000 N tensile load

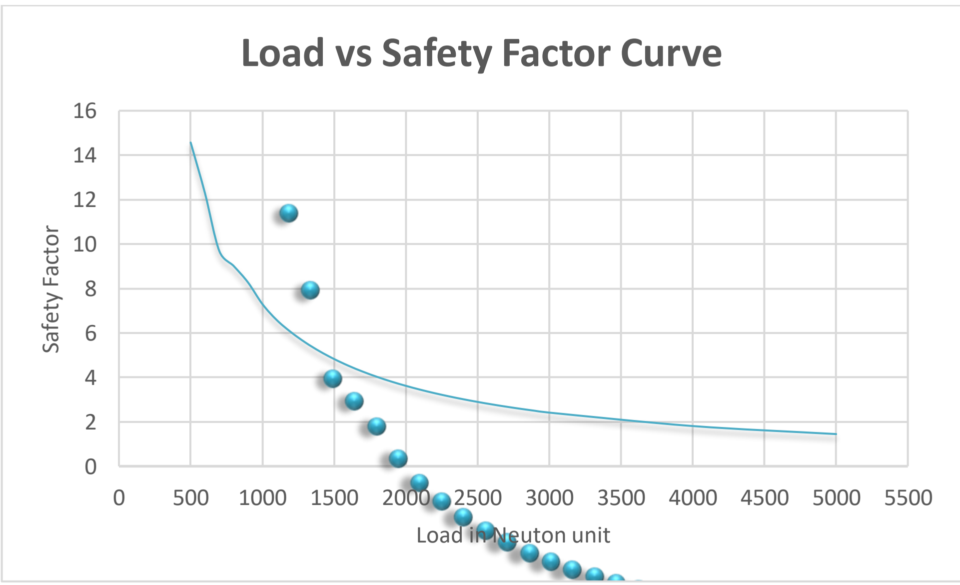

Fig. 12 The Safety factor curve of tensile loads on the handle

4.2 Finite Element Analysis on the Frame

The static structural simulation under different loads has been done. Loads have been applied to the main load-carrying base showed in figure-1. The wheels were fixed and placed on a fixed ground to observe the real load application.

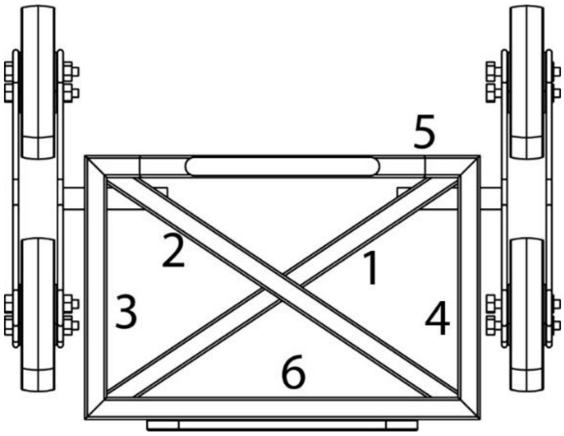

Fig. 13 Loads Applied on the 1 and 2 Face along –Y direction

From the below figure 14, the safety factor for safe loading has been found as 1.0044 which means that around 1900 N loads can be stored in static condition on the main load-carrying structure.

The safe weight = $^{1900}/_{9.81} = 193.67 \cong 194\ kg$

The structure is more than enough strong & the design is capable to carry an extensive amount of load. But an adult, as well as a healthy person, cannot carry the load more than 30 kg in normal condition [29]. The weight of the cart will be added with the load which is a constant.

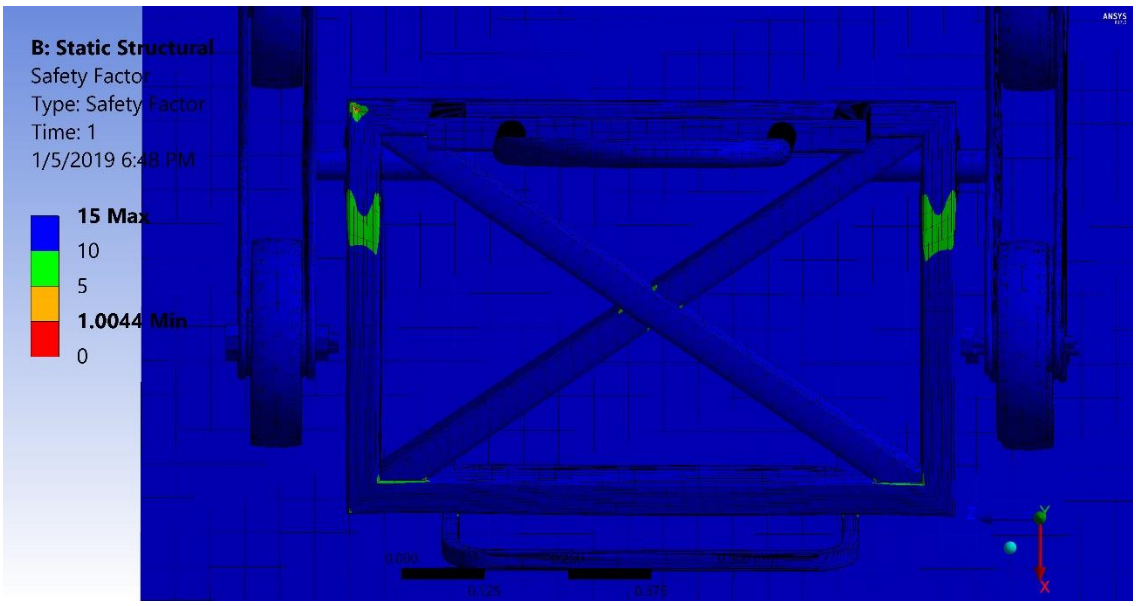

Fig. 14 Factor of safety distribution under 1900 N load in static condition

The blue color regions of the cart will not affect even at the factor of safety close to 1. This implies better sustainability of this product although the total load is not possible to exceed 500 N because this is beyond than the mean value of force that can be exerted by a human.

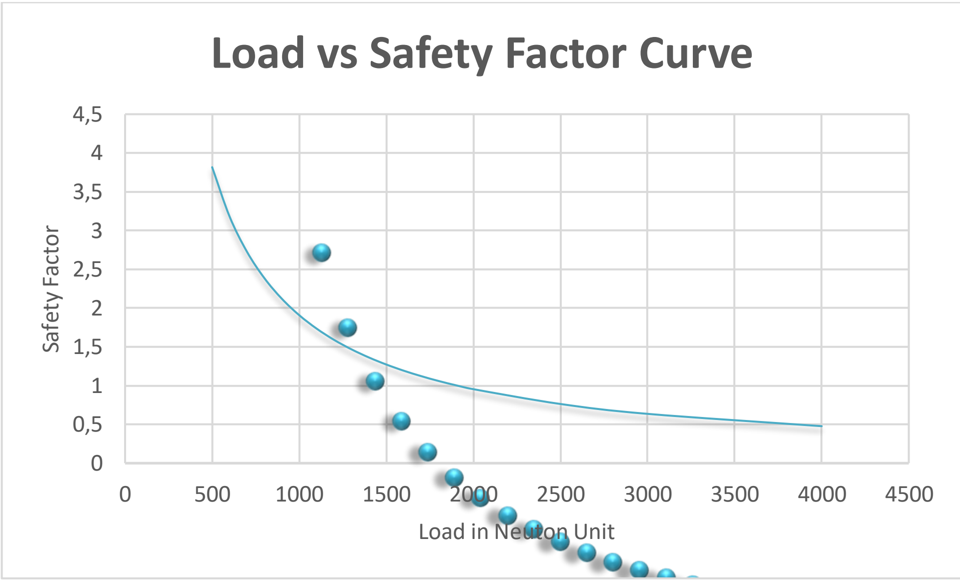

Fig. 15 The safety factor curve for different loads in static condition

In the dynamic analysis of load first, the mechanism should be understood. The cart will be pulled at an inclined angle with the horizontal. This angle depends upon the height of the person who is pulling the cart. Generally, the inclined angle is 40-65°. During carrying loads, it is better to tie the goods with ropes.

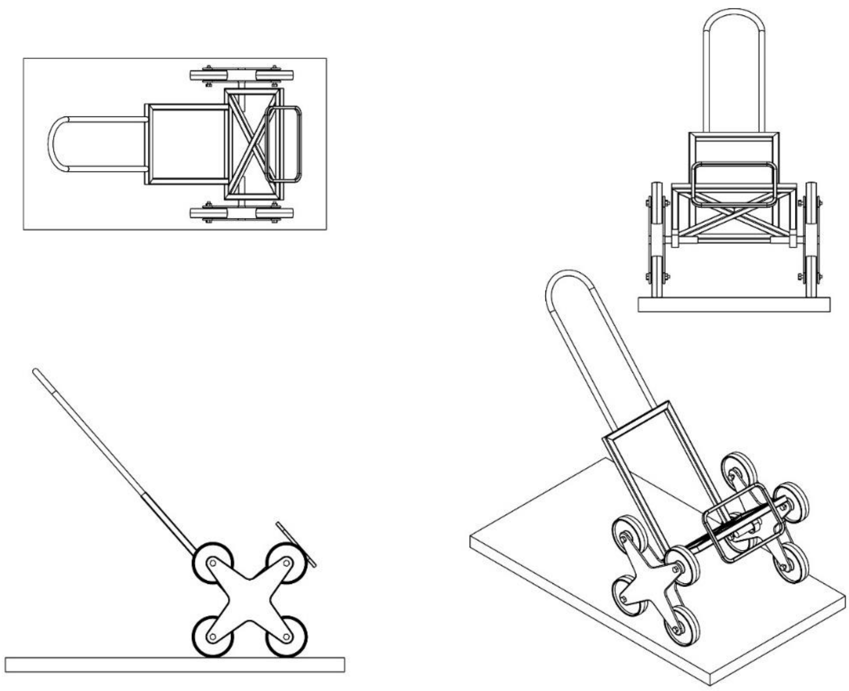

Fig. 16 The load carrying condition of the cart (Inclined with horizontal)

The frame members are available from local vendors and there are so many heavy metal industries who produce standard size and shape structural members. Weight reduction or any other type of optimization will need extra tooling as well as machine and operator. This will increase the manufacturing cost to a significant amount even the project may not be feasible for that. The design of the frame is already optimal considering the overall cost.

4.3 Finite Element Analysis on the Wheel

The wheels were tested with finite element analysis under the maximum load that may be carried on the load. The wheels will have to carry the load of the goods and also the weight of the cart. So wheels were tested under 2000 N force on the rotation circumference and the bolt inserting bore was fixed during the analysis. The material of the wheel will be ABS plastic.

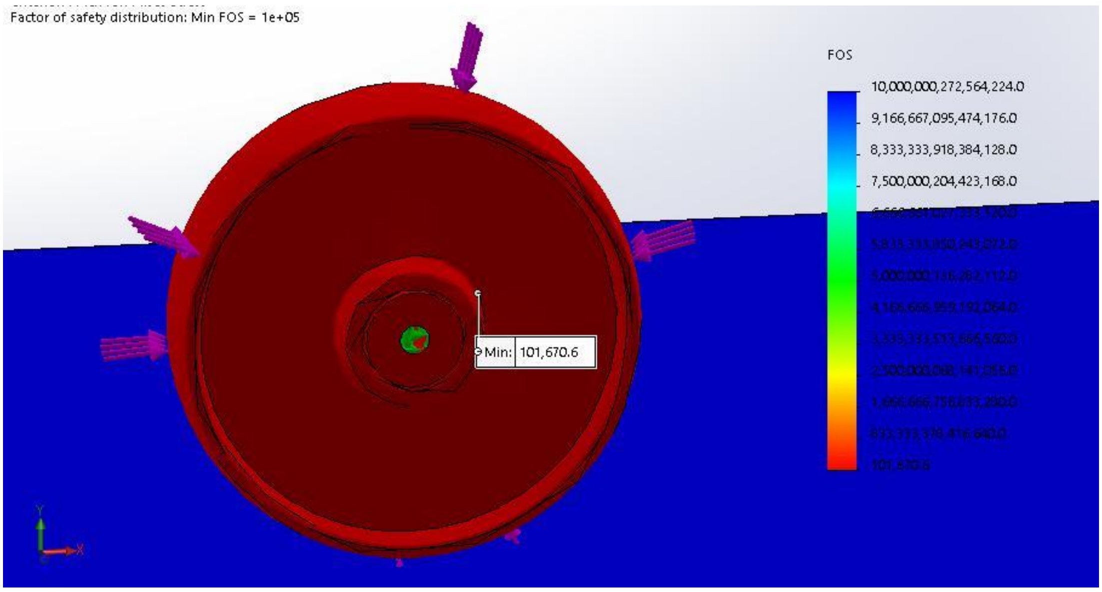

Fig. 17 Factor of safety of a wheel under 2000 N load

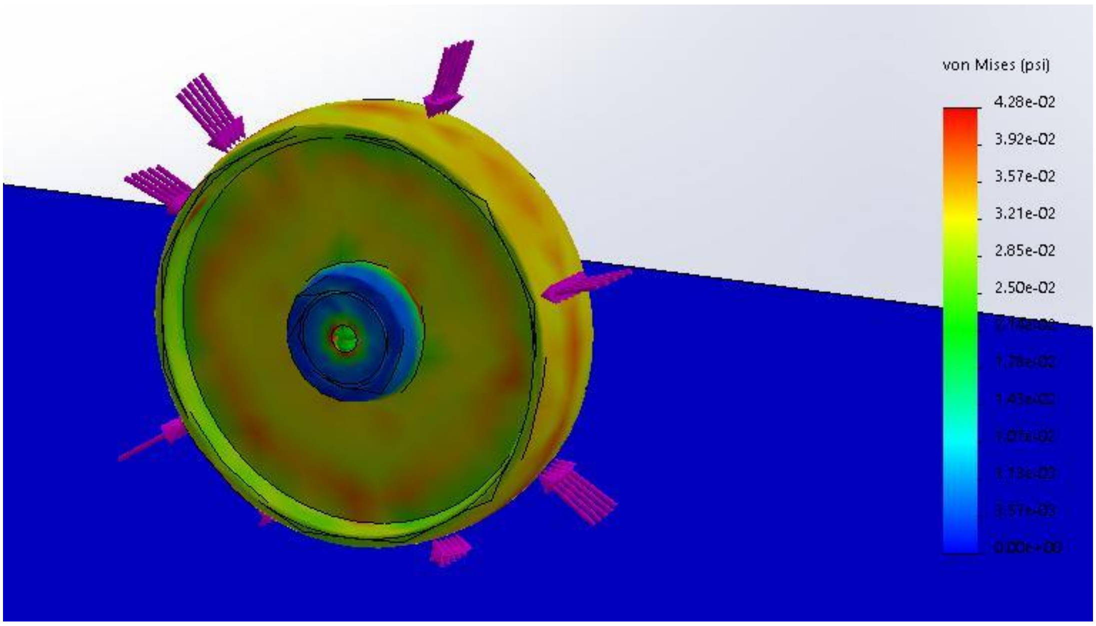

Fig. 18 Von-Mises stress distribution under 2000 N load

It is seen that the maximum load even cannot affect a single wheel. The design of the wheel can be optimized by reducing some materials. The wheels will be manufactured by the injection molding process. The cut wholes showed in figure 19 can be produced from the core of the mold. So the machining cost may raise a little while making the mold but this will reduce a lot amount of material as well as cost in mass production.

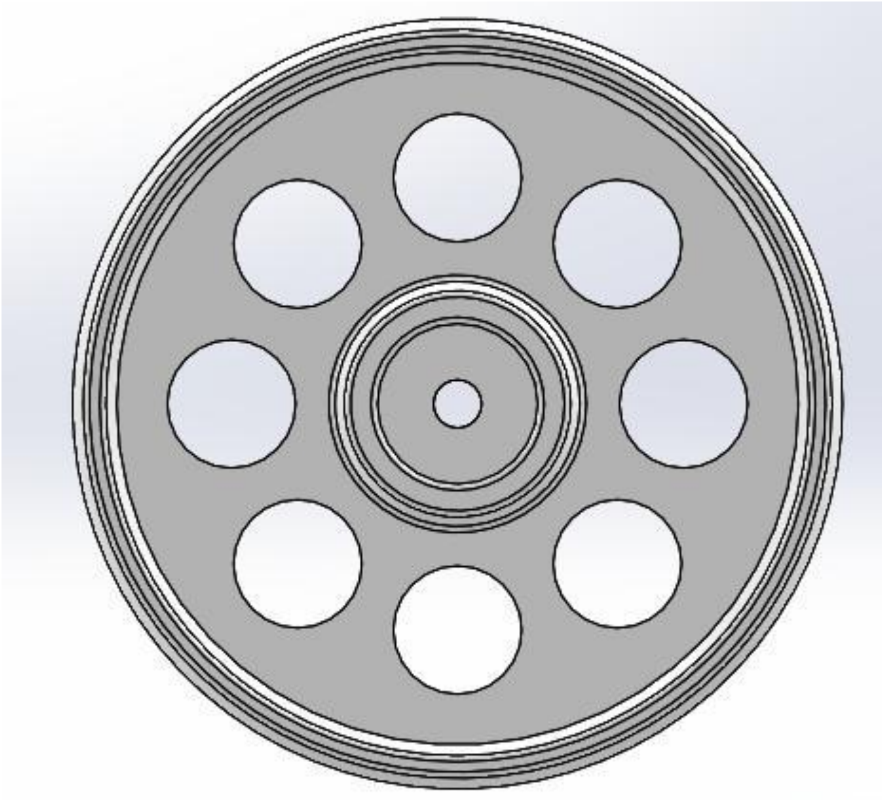

Fig. 19 Optimized design of the wheel

CONCLUSION

In this stair climbing cart design cost, material availability, production process availability, human factors, customer requirements, etc. all factors have been equally considered. The newly added features in this design will eliminate stress on fingers, hands, backbone & corresponding body parts. There is a direct relationship between the pulling angle and pulling force. The pulling angle varies according to user height. This design can carry a satisfactory range of load that is determined from the structural analysis. This design is unique than others in the pause-rest feature which provided the function to keep the cart standing between two stairs by keeping two backward wheels on a stair and other forward wheels on the next stair. In this design, all constraints have been satisfied & also the strength, durability & longevity of the structure have been increased which has been tested in the structural simulation. Carrying heavy loads over stairs may cause injuries to a human being such as back pain. This stair climbing cart eliminates human effort to carry goods. This research will help interested manufacturers who want to commercially produce it for mass customers. The manufacturing process and bill of material will help the manufacturers to determine the required machines, the number of operators, required space and finally the cost of the product.

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