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City vehicle Doors / Car park-friendly doors project

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Abstract:

This report focuses on the concept design of the innovative mechanism for the door opening in the car within the distance of 2500 mm. The research commences by exploring various mechanisms employed in different types of car doors that are currently in use. The initial design procedure followed includes the FAST diagram, Kano model, QFD and Morphological chart analysis. The application of these methods facilitated the creation of two conceptual design based on upward counter clockwise rotation and the sliding mechanism. The AHP (analytical Hierarchy Process) has been used to evaluate and prioritize among the designs based on their criterion and sub criterion. The final concept generated incorporates the hinge mechanism that pivots in a anticlockwise direction towards the front of the car's body with the extension of linear actuator. The DFM and DFA has been carried out to optimize the production process, cost by making design easier to manufacture and assemble. The selection of materials and the manufacturing process is also taken into account. The FEA analysis has been performed to find out the stress and displacement on the designed hinge mechanism where the factor of safety was found to be 4.56. The FEA model has been validated with the hand calculation and has been optimized to reduce the stress in the highly stressed part of the mechanism. The DFMEA analysis has been conducted to foresee and minimize possible risks and failure of the mechanism before the design phase. The cost of the self-designed parts was analysed based on factors such as the material used, the manufacturing cost, assembly cost and the volume of a material and was found to be only £199.47. This design process prioritizes sustainability by taking into account environmental considerations, financial profitability, and social equity. Eventually, the ergonomics focuses on the sufficient opening of the car door for easy ingress and egress, door handle location, sound isolation and the pocket structure in the car door.

Overall, the complete design of the new hinge mechanism for the car door has been developed considering almost every factor that is required in the design process to successfully achieve the result.

Contents

1. **Introduction** ... 2
2. **Market Analysis/Literature Review** ... 3
   2.1. **Concluding literature review:** ... 12
3. **F.A.S.T Diagram** ... 13
4. **Kano Model** ... 14
5. **QFD (Quality Function Deployment)** ... 16
6. **Morphological Chart Analysis** ... 17
7. **Concept Generation** ... 23
8. **PCC (Pairwise Comparison)** ... 24
9. **Conceptual Designs** ... 25
   9.1. **Conceptual Design 1** ... 25
   9.2. **Conceptual Design 2** ... 26
10. **AHP (Analytical Hierarchy Process)** ... 27
11. **Final Design** ... 28
    11.1. **Mechanism- Closed State of Door** ... 28
    11.2. **Mechanism – Half Opened State.** ... 29
    11.3. **Mechanism – Full Opened State.** ... 30
    11.4. **Mechanism- Closing after fully opened** ... 31
    11.5. **Door Opening Speed** ... 31
    11.6. **Manual Door Operation** ... 32
12. **Design-Exploded view of crucial components** ... 33
13. **DFM (Design for Manufacturing)** ... 34
14. **Material selection** ... 36
15. **DFA** ... 38
    15.1. **Assembly Structure Diagram** ... 40
16. **Costing** ... 41
17. **Sustainability** ... 43
18. **FEA of Hinge, modal validation (Hand Calc.) and optimization** ... 45
    18.1. **Finite Element Analysis of Hinge** ... 45
    18.2. **Results of FEA analysis** ... 47
        18.2.1. **Factor of safety (FoS)** ... 48
    18.3. **Modal Validation** ... 48
        18.3.1. **Reaction Forces (FEA)** ... 48
        18.3.2. **Validation with hand calculation** ... 49
    18.4. **Modal Shape Analysis** ... 50

18.5. Optimization of Hinge Designs 51
18.5.1. Optimization Result. 52
18.6. Concluding FEA Analysis and Design Optimization 53
19. DFMEA 54
20. Ergonomics 58
21. Conclusion 59
22. References 60
23. Appendix 65
23.1. Appendix 1: Material Comparison Graphs used to select materials. 65
23.2. Appendix 2: Exploded View of Hinge and Linear Actuator 66
23.3. Appendix 3: Tables and Charts used to create DFM. 68
23.4. Appendix 4: Tables and Charts used to create DFA. 70
23.5. Appendix 5: AHP, Design selection criteria 72
23.6. Technical Drawing of Hinge Components 77

List of Figures

Figure 1: *Common car door and its hinge mechanism* 3
Figure 2: *Shows a view of the suicide doors.* 4
Figure 3: *Type of hinges used for a suicide car door.* 4
Figure 4: *Hinges used for Scissor doors displaying how this mechanism works.* 5
Figure 5: *View of the butterfly doors* 6
Figure 6: *View of dihedral helix doors.* 7
Figure 7: *Hinge mechanism used for the dihedral helix car doors* 7
Figure 8: *View of the swan car door in a Aston Martin Vantage.* 8
Figure 9: *Shows how a sliding door operates* 9
Figure 10*: Hinge used for sliding car door.* 9
Figure 11: *Display of canopy doors function* 10
Figure 12*: Display of the Gull Wing Doors* 10
Figure 13*: Hinge used for gull wing doors.* 11
Figure 14: *Shows pocket doors design* 11
Figure 15: *Fast Diagram* 13
Figure 16: *QFD (Quality Function Deployment).* 16
Figure 17: Conceptual designs and mechanism developed for the project. 23
Figure 18: Main conceptual design of the project, showing the hinge parts and its operation. 25
Figure 19:*View of door with connection.* ***Figure 20:*** *Close up view of hinge connection.* 26
Figure 21: *Door lateral view during closed.* ***Figure 22:****Rear view of the mechanism during closed.*
Figure 23: *Top view of the mechanism closed.* 28
Figure 24: *Door lateral view during closed state.* ***Figure 25:*** *Rear view of the mechanism.*
Figure 26: *Side view of the mechanism* 29
Figure 27: *Link for movement.* 29

Figure 28: *Mechanism lateral view during full opening.* ***Figure 29:*** *Rear view of the mechanism.*
Figure 30: *Top view of mechanism.* 30
Figure 31: *Free body diagram of the hinge* ***Figure 32:*** *Distance between rotation* 32
Figure 33:*Design-Exploded View of Crucial components.* 33
Figure 34:*Young's modulus and Price graph of various metals* 36
Figure 35: *Yield Strength Vs Density of various metals.* 36
Figure 36:*Figure showing specification of composite Neoprene/EPDM.* 37
Figure 37: *Assembly Structure Diagram.* 40
Figure 38: *Shows the complete mechanics of the hinge.* 42
Figure 39*:Three Pillar of Sustainability* 43
Figure 40: *Graph showing energy needed for the primary production of certain metals.* 43
Figure 41: *Graph showing recyclability and young's modulus of zinc alloy and steel.* 44
Figure 42: *Display the mesh and load applied in the hinge.* 45
Figure 43: *Plot mesh convergence displacement against element size, 5,7and 15 (mm).* 46
Figure 44: *Plot mesh convergence stress against element size, 5,7and 15 (mm).* 46
Figure 45:*Displacement analysis in Hyper Works. (mm).* 47
Figure 46:*Stress analysis in Hyper works. (MPa).* 47
Figure 47: *Reaction forces at the nodes found using Hyper works.* 48
Figure 48: *Free body diagram of the hinge.* 49
Figure 49: *Modal Shape of hinge at frequency 97.244 Hz.* 50
Figure 50: *Modal Shape of hinge at frequency 289.1 Hz.* 50
Figure 51: *Modal Shape of the hinge at frequency 1097 Hz* 51
Figure 52: *Counter plot showing density change during optimization.* 51
Figure 53: *Iso View of counter plot showing density change during optimization.* 52
Figure 54: *Displacement analysis after design validation.* 52
Figure 55: *Stress analysis after design validation.* 52
Figure 56: *Design showing the width* ***Figure 57:*** *Design showing height of the* door. 58
Figure 58: *Design showing the height from bottom of the door to handle.* 58
Figure 59: *Fracture Toughness Vs Density graph of different Metals and Composites.* 65
Figure 60: *Yield Strength Vs Price of Elastomers.* 65
Figure 61; *Maximum temperature Vs Recycle of various Elastomers.* 66
Figure 62: *Figure showing the exploded view of hinge and small linear actuator.* 66
Figure 63: *Figure showing the exploded view of bigger linear actuator.* 67
Figure 64: *Figure showing Bill of Material.* 67
Figure 65: *Basic Processing Cost.* 68
Figure 66: *Geometric Complexity Graph index for AM* (C_c). 69
Figure 67: *Coefficient Graph for AM* (C_S). 69
Figure 68: *Tolerance Coefficient Graph (Ct).* 69
Figure 69: *Surface Finish Coefficient for AM* (C_f). 70
Figure 70: *Design for Assembly criteria for handling and penalties.* 70
Figure 71: *Showing the values for component insertion penalty.* 71
Figure 72: *Selection criteria's to develop AHP.* 72

List of Tables

Table 1: *Kano Model.* 14
Table 2: *Morphological Chart Analysis* 17
Table 3: *Table showing pairwise comparison.* 24
Table 4:*DFM table showing the manufacturing cost of the hinge.* 35
Table 5: *DFA table showing the Assembly cost of the hinge.* 39
Table 6: *Screw, Nuts and Bolts quantity and cost.* 42
Table 7: *Mesh convergence analysis of stress and displacement with mesh size of 5, 7,15 (mm).* 46
Table 8: *Results of the reaction forces obtained using Hyper works.* 48
Table 9: *reaction forces obtained from Hand Calculation* 49
Table 10: *Design Failure Mode and Effect Analysis of hinge mechanism.* 54
Table 11: *Waste Coefficient table (Wc) with marked values for all 10 components.* 68
Table 12: *Relative cost data materials mentioned in table(), material processing sustainability (C_{mp}).* 68
Table 13: *Tables with the AHP values obtained.* 72

City vehicle Doors / Car park-friendly doors project

1. Introduction

A car door is an essential component in any automobile, which functions for the ingress and egress of the passenger to and from the vehicle. Furthermore, it is crucial for passenger's safety as it minimises the impact of side collisions. There are several mechanisms and systems for operating car doors available for different car models but the most popular and adaptable one is the convectional door. The convectional doors have simple mechanism of hinges, cost-effective and are considered safe due to their structural integrity and side impact protection (high level of reinforcement and side impact beam) in comparison to other mechanisms such as butterfly door, scissor door, Gull wing door. The conventional door is typically hinged and opens away from the car body however this design is not suitable for use in tight parking spaces as it doesn't allow for there to be a sufficient opening to enter and exit the vehicle.

Therefore, the aim of this report is to outline the process of designing a car door operating system for the range rover 2022 model width 2200mm (LH mirror to RH mirror) trying to be parked in a car parking space of 2500mm which is the size of a European car park space. The design should accommodate for a 95th percentile human operating the door while not obstructing the rear load space. Additionally, the door should have a quality finish appearance and a smooth operation with a premium feeling working at an acceptable speed and noise level. The design should consider the AB flange compression direction and engagement and the option to have both a manual and powered operation. This will be achieved through various studies of the different mechanisms of the door with the use of various design analysis strategies; fast diagram, KANO model, morphological analysis and QFD (quality function deployment) to explore the different aspects of car door design followed by manufacturing evaluation techniques including DFM, DFA, DFMEA to reduce costs, prevent defects and increase reliability and safety of the car door considering the sustainability of the design.

2. Market Analysis/Literature Review

The design of car doors is continuously being adapted and enhanced to optimise the design. The task of creating an innovated mechanism for a car door was approached by investigating different mechanisms for operating the door and different door designs and evaluating how well they solve the problem and their limitations. (Pumilia, 2020)

Conventional Door:

***Figure 1:** Common car door and its hinge mechanism (howacardoorsworks.com, nd)*

Mechanism: This is the most common type of door used in cars whose opening and closing is via hinge. Hinges are fixed in the front end of the pillars vertically with the ground. Conventional car doors operate using a simple mechanism involving hinges, a latch system, a handle, and a check strap. The hinges are attached to the door and car body at the A (front doors) and B (rear doors) pillars and allow the door to be swung open while supporting the weight of the door. The latch system allows for the door to be opened and locked by moving the latch up and down respectively. The handle, when pulled allows you to open the door by moving the latch up.

Advantages of Conventional Doors:

1. It is safer in terms of safety. In case of opened door during the car's motion, the aerodynamics of the car will force the door to its closure.
2. Provides good space for entry and exit.

Disadvantages of the Conventional Doors:

1. It occupies more lateral space which creates problems opening the door in compact and tight parking areas.
2. The front door is longer than the rear door, and this unequal distribution results unusual proportion.

Suicide Doors:

Figure 2: *Shows a view of the suicide doors (Axom, nd).*

Figure 3: *Type of hinges used for a suicide car door (Ebay, Brand New Four Suicide Door Heavy Duty Hidden Hinges Rat Rod 2 Door Kit Weld In, nd).*

Mechanism: The hinge mechanism is used in suicide door which consists of 2 hinges mounted vertically to the ground. The hinges allow the door to be swung open. The front doors operate similarly to conventional doors, in contrast the rear door has hinges attached at the rear end of the car body at the C pillar so that they open in the reverse direction from the front doors. A latch mechanism is employed to maintain the door closed. The latch normally consists of a latch assembly installed on the door and a striker plate located on the automobile body. The latch assembly latches onto the striker plate when the door is closed, securing the door in place.

Advantages of the Suicide Doors:

1. It provides enough space for the passengers and the driver to enter the car.
2. The suicide door can be designed without the B pillar which creates huge openings for the ingress and the egress.

Disadvantages of Suicide Doors:

1. The aerodynamic structure of the car could force the door to open during high speed.

2. The rear door cannot be opened until the front door is closed for the car without B pillar.
3. It occupies more lateral surface for the maximum opening of the door.
4. Due to the adjacent opening of both the front and the rear door, it seems awkward when using both doors simultaneously.

Scissor Doors:

Figure 4: *Hinges used for Scissor doors displaying how this mechanism works (Ebay, Vertical Door Hinges Bolt Kit Butterfly 90° Car Doors Universal Lambo Scissor, nd).*

Mechanism: Scissor door mechanisms rotate upward and outward together, opens like a pair of scissors. It is also based on a hinge mechanism. Two parallel links that allow the door to open vertically are attached to the car body and allow it to pivot about a central axis. The pivot points are located at the base of the A-pillar and the bottom of the door which allows the door to move in a scissor-like motion as it opens and closes. Similarly, the electric motors and hydraulic or pneumatic actuators are used in conjunction with a motorised system to lift the doors.

Advantages of Scissor Doors:

1. *Aesthetics*: Scissor doors offer a distinctive and eye-catching design that can enhance a car's appearance and appeal.
2. *Space-saving*: Scissor doors open vertically, making better use of available space in confined parking spaces.
3. *Improved access*: In constrained parking spaces where conventional doors might not be able to open completely, scissor doors improve access to the vehicle.

Disadvantages of Scissor Doors:

1. Complex mechanism: To operate properly, the scissor door mechanism may need careful design and maintenance.
2. Limited applicability: Because of their dimensions, shapes, or design specifications, scissor doors might not be appropriate for all kinds of vehicles.

3. Increased cost: Due to the complexity of the mechanism and the materials used, scissor doors are frequently more expensive than conventional doors.
4. Reduced structural rigidity: Scissor doors can also weaken the car's overall structure, leaving it more susceptible to damage in an accident.
5. Difficulty in entering and exiting: Especially for passengers who are unfamiliar with the mechanism or for those who have mobility issues.

Material:

To provide the required strength and durability, the scissor mechanism is typically made of metal, such as steel or aluminium.

Butterfly Doors:

Figure 5: *View of the butterfly doors, similar to scissors but hinge is located to move the door outward (Stevens, 2022).*

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Mechanism: The mechanism of the Butterfly door consists entire use of a complex hinge design. The hinge mechanism consists of two arms that are attached by a pivot point. One arm is sustained with the car body is fixed horizontally on the pillar A of the car while the other is attached to the door itself. As the door is opened, the two arms pivots around the central point, causing the door to lift upwards and outwards. A hydraulic strut or gas shock absorber is also a common component of butterfly door systems to guarantee that the door is stable and secure when it is opened. This serves to moderate the door's speed and motion, preventing excessive swing or slam closing.

Advantages of the Butterfly Doors:

1. There is enough space for the entry and exit as the doors moves straight up.
2. It occupies less lateral space than a conventional door, which is advantageous for parking spaces.

Disadvantages of the Butterfly Doors:

1. Parking under the lower ceiling building could be a problem.
2. Opening doors during roll-over accident is tough.
3. Such advanced technology is more constrained by structural factors.

Dihedral synchro helix doors:

Figure 6: *View of dihedral helix doors (Stevens, 2022).*

Figure 7: *Hinge mechanism used for the dihedral helix car doors (Swadeology., nd).*

Mechanism:

The dihedral synchro helix mechanism utilises a combination of dihedral and helix movements to open and close the door. This is achieved by the complicated hinge design which has a helix cut into the hinge to allow the rotation. Several coordinated motions are involved to open and close the door. When the door is opened, it turns outward and upward. This is possible due to the hinge design that uses gears to adjust the position of the door simultanously as its pulled outwards so that it can rotate in the desired position. When the locking mechanism is disengaged, the hydraulic or pneumatic strut aids lift the door up and away from the car. This system uses a simple latch mechanism and door handle similar to that of conventional doors.

Advantages:

1. Aesthetically, the car looks futurist with the doors rotating 90 degrees.
2. They offer a wide range of space to get in and out of the car.

Disadvantages:

1. Expensive to repair as these doors are connected to a very technical hinge.
2. The maximum door opening occupies larger vertical area such as parking in the lower ceiling building will be difficult.

Material.

Few luxury vehicles like the *Koenig egg* doors and main body are made of carbon fibre, an expensive material and cannot be recycled.

Swan Doors:

Figure 8: *View of the swan car door in a Aston Martin Vantage (AUTOFREAK, 2015).*

<u>Mechanism</u>: Swan doors operate similarly to conventional doors as they use same hinge system to open the door but with the adjustment of the hinge being placed higher allowing the door to open upward and outward at a wider angle in a curved motion. A central locking system is used for this system.

<u>Advantages:</u>

1. These doors make the car look most stylist.
2. They are very similar to the common doors which makes its use very familiar for all drivers.

<u>Disadvantages</u>:

1. These doors do not offer any improvement in how to access as its mechanics is similar to common car doors.
2. Although it occupies lesser lateral space than conventional door, opening door is still a problem in the tight parking areas.

In general, these doors do not offer a relevant advantage to common doors used in the majority of cars, the only difference is that they make the cars looks more luxurious.

<u>Material</u>:

Material used in these doors are most of aluminium-alloys.

Sliding Doors:

Figure 9: *Shows how a sliding door operates (AUTOFREAK, 2015).*

Figure 10*: Hinge used for sliding car door (Procarparts., nd).*

Mechanism:

A sliding door's mechanism normally consists of a track setup that enables the door to move horizontally along the side of the car. Two tracks make up the track system, one installed on the door and the other on the body of the car. The door can travel back and forth smoothly on the tracks, which are typically composed of metal and equipped with rollers or ball bearings. This mechanism can be powered by using of cables that can pull the door open and close and a motor to provide the force to automatically operate the door in conjunction with safety sensors. Additionally, it uses a traditional latch system and door handle to lock the door.

Advantages:

1. Sliding doors are easy to use and, its sliding system is helpful to reduce car park spaces, may be the best in the compact car parking areas.
2. These doors can offer a wide opening with is useful and comfortable for ingress and egress and also to introduce goods in the car.

Disadvantages:

1. The tolerance of a door mechanism is smaller than that of a typical hinged door.
2. The door system is difficult to repair if some rolling bearing fails, door replacement might be required.

3. Due to rolling system, there is high chance of noise problem in opening and closing the door.
4. This mechanism doesn't seem to be attractive in the aesthetic point of view.

Material:

Most of the doors are manufactured with aluminium-alloys and uses recycled materials.

Canopy doors:

Figure 11: *Display of canopy doors function (Autojosh., 2019).*

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Mechanism: The canopy door mechanism consists of hinges placed either at both lateral sides or the frontal sides of the car which allow the door to be swung upwards. This mechanism is usually installed in the doors of the jet's fighters, this door works as whole door, hinged in both lateral sides or in the frontal sides of the car, top root and windscreen moves upward and forward.

Advantages:

1. These doors normally do not have obstruction problems as they open upward and forward.
2. These models do not have side doors with mean that the windscreen can be extend giving a view of 180 degrees.
3. A more effective use of the climate control inside of the car.

Disadvantages:

1. This model is dangerous if in an accident the car rolls over the driver will have problems to get out.
2. In case of raining, snow or any other climate circumstance the interior of the car will be affected.

Gull Wing Doors:

Figure 12: *Display of the Gull Wing Doors (AUTOFREAK, 2015).*

Figure 13*: Hinge used for gull wing doors (Johnnylawmotors., nd).*

<u>Mechanism</u>: Gull wing doors operate similarly to scissor door with the use of a hinge system however the hinges are positioned on the roof of the vehicle rather than the side pillars. The hinge has a 'swan-neck' design which allows it to open outward then upwards which helps open the door in tight spaces. There is also a hydraulic or pneumatic strut that is used to help lift the door, this can be replaced with the use of a control arm that is attached to the car body. A traditional latch system and door handle is used in this mechanism.

<u>Advantages</u>:

1. This design is practical and beneficial in compact and tight parking areas.
2. It provides enough space to ingress and egress and only requires about 27.5 cm side clearance.

<u>Disadvantages</u>:

1. Similar to the Butterfly door, the roll-over accident makes it tough to escape out from the car. But the Mercedes SLS addressed this issue by incorporating explosive bolts into the hinges that would explode in the case of a rollover.
2. The absolute opening of the door is not possible in the lower height ceiling garage or parking areas.
3. High-cost technology: both manufacturing and design are costly.

Pocket Doors:

Figure 14: *Shows pocket doors design (Stevens, 2022).*

<u>Mechanism</u>:

The pocket door uses a sliding mechanism consisting of a track and rollers allowing to slide the door into a pocket on the car body. The track is typically installed above the doorway and runs parallel to the frame. This mechanism can be powered using cables and a motor. The only difference with sliding doors is pocket doors glide along its width and vanishes into a bodywork of the car while it is open. It uses a simple latch system and door handle for the locking mechanism.

Advantages:

1. Sliding mechanism makes it easy in small space parking areas.
2. Unlike sliding doors,
3. Unlike sliding doors, it looks more advanced an aesthetic point of view.
4. Wider opening makes the ingress and egress easy.

Disadvantages:

1. Due to the sliding mechanism, noise can be expected.
2. Repairing the door might sometimes need removing the body frame of the car which serves as a pocket.
3. The tolerance of a door mechanism is smaller than that of a typical hinged door.

Materials used in Automobile bodies:

(Davies., 2012)**,** this book offers a very specific description of the material selection for the main materials used to build a body structure car such as, steel, aluminium, magnesium, polymers and composites. Explanation of advance manufacture process for Steel and Aluminium Formability, as the majority of the car parts are shaped by pressworking. Pressworking has its limitation in the materials though there are several publications and conference papers on various design issues and related materials, these reference works tend to concentrate on certain materials, test procedures, or numerical simulations. Few have attempted to evaluate all the realistic candidate materials in one volume in terms of design, fabrication, and appropriateness for component production, corrosion resistance, and environmental features.

2.1. Concluding literature review:

The use of Suicide and Swan doors poses a similar problem as Conventional doors due to the fact that the opening of the door will be obstructed in tight spaces therefore it is not a suitable mechanism. Canopy doors require enough space above the car to provide a comfortable opening which would not be available in low ceiling indoor parking garages. In addition to this the complexity of the mechanism makes it not practical for its function. The Butterfly doors also occupy excessive lateral space during its opening. All these mechanisms were disregarded and taken out of consideration for the design as they would fail to meet the requirements of the design specification.

When taking into consideration the conditions of the problem the most suitable mechanisms would be Dihedral synchro helix door, Scissor door, Gull wing door, or Sliding doors. The mechanisms for Dihedral synchro helix, Scissor and Gull wing doors all have combined movement of vertical and horizontal translations which allow the door to move through an optimal path from close to open. This mechanism can operate within the limited space of tight car park spaces. Additionally, the door rotates as it's pushed up to occupy minimal space above the car making it appropriate for use in low ceiling parking garages. Similarly, the sliding doors fulfils most of the requirements for the design specification but due to its noisy rolling system, it couldn't be the best mechanism to be proceeded with, but the idea of sliding doors could also be considered, and the changes could be made for the innovative mechanism of the door.

3. F.A.S.T Diagram

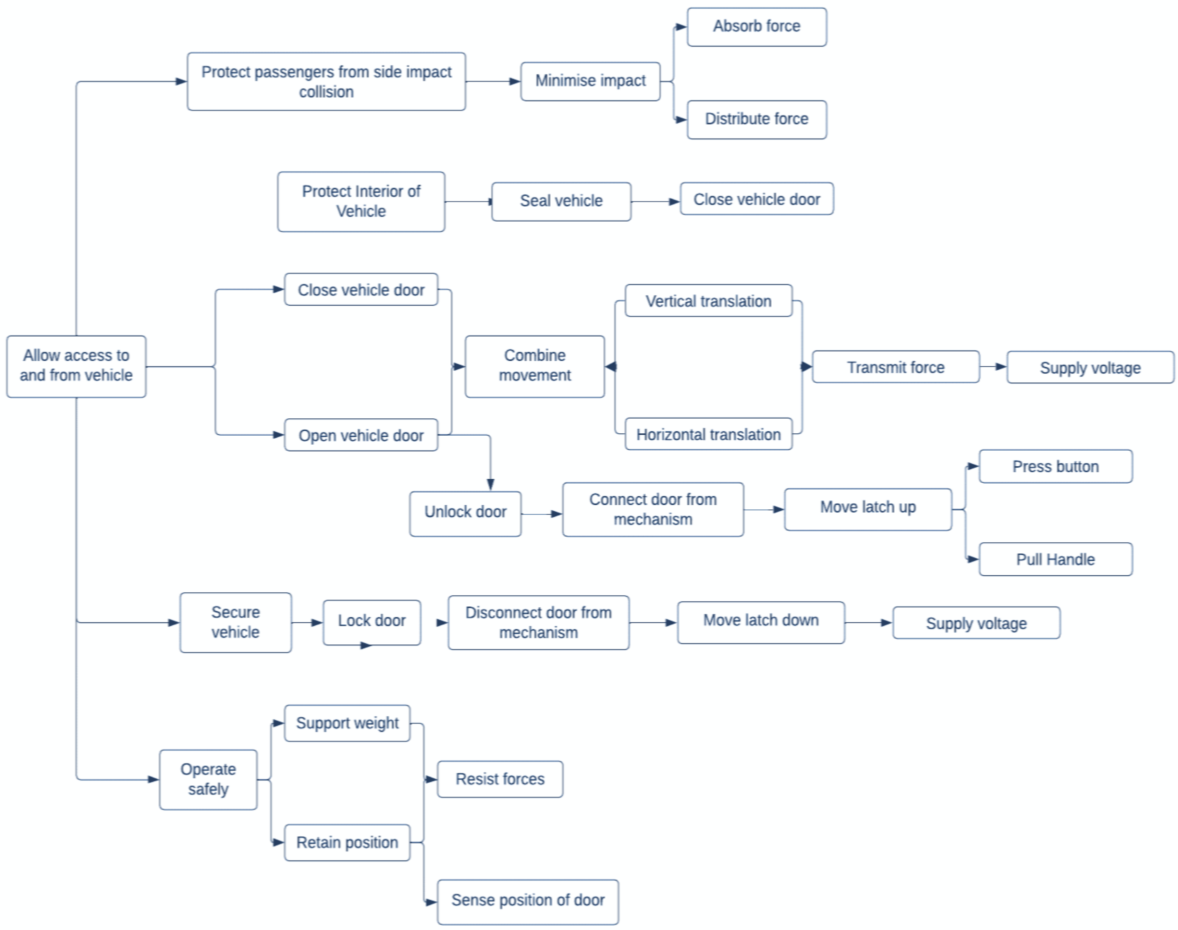


Figure 15: *Fast Diagram.*

F.A.S.T (Function Analysis System Technique) diagram provides a structured approach to understanding complex systems and identifying potential solutions. It displays all functions of a system, going right the diagram will show how each function is achieved and going left it shows why each function is useful. FAST Diagram is considered in order to recognise how each function will be achieved in the system; this is crucial to make sure the system being designed performs all functions. The primary function of the car door system is to allow access to and from the vehicle however it has very important secondary functions such as protecting passengers from side impact collisions. With the knowledge of how a car door performs its functions, the major aspects of the design such as a locking and unlocking system, opening mechanism and passenger safety considerations have been identified.

4. Kano Model

Table 1: *Kano Model.*

		FUNCTIONAL										DYSFUNCTIONAL									
		If you can have this feaure, how do you feel?										If you cannot have this feaure, how do you feel									
		No. of questionnaire										*No. of questionnaire*									
No.	**Feature**	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**	**#9**	**#10**	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**	**#9**	**#10**
1	*Low vibrations*	L	L	N	L	L	E	L	E	L	L	D	T	N	N	T	N	D	D	D	D
2	*Shut the lines gaps when close*	L	L	L	L	E	E	L	E	L	L	D	D	D	D	D	D	D	D	D	D
3	*Acceptable speed*	L	N	E	L	N	N	E	N	L	N	D	T	D	N	D	D	N	T	N	D
4	*Low noise level*	L	L	N	L	L	E	L	E	L	L	D	T	N	D	T	D	D	D	D	D
5	*Quality finish appearance when closed or open*	L	N	L	E	L	E	L	N	L	L	D	N	D	N	D	T	D	N	D	T
6	*Stay open on the slope*	L	L	N	N	L	L	L	N	L	L	D	D	N	N	D	D	T	N	D	T
7	*Easy to open and close*	L	L	L	E	E	L	L	E	L	L	D	D	D	T	N	D	D	T	D	D
8	*The ability to open the Door when parked in a space of 2500mm*	L	L	L	L	E	L	L	L	E	E	D	T	T	D	N	T	D	T	D	D
9	*Sealing*	L	L	N	L	L	N	E	N	L	L	D	T	N	D	T	N	D	N	T	D
10	*Premium feeling (smooth operation)*	L	N	E	L	L	E	L	N	L	L	T	D	D	D	D	T	D	N	E	E
11	*AB Flange compression direction and engagement*	N	L	N	L	E	L	N	L	L	L	N	T	N	D	N	T	N	D	T	D
12	*Give unobstructed access to rear load space.*	L	N	N	L	N	E	L	N	L	L	N	T	N	D	N	T	D	N	D	D
13	*Manual operation*	N	L	E	N	L	E	N	L	N	N	N	D	T	E	D	N	T	N	N	N

		Performance									
		No. of questionnaire									
No.	**Feature**	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**	**#9**	**#10**
1	*Low vibrations*	P	M	I	P	P	P	P	P	P	M
2	*Shut the lines gaps when close*	M	M	A	P	A	P	P	P	P	M
3	*Acceptable speed*	P	P	M	P	I	I	P	P	M	M
4	*Low noise level*	P	M	P	P	M	P	P	I	P	P
5	*Quality finish appearance when closed or open*	P	A	A	P	I	P	I	M	M	M
6	*Stay open on the slope*	P	P	I	I	M	M	P	P	M	M
7	*Easy to open and close*	M	P	P	I	P	M	M	P	M	M
8	*The ability to open the Door when parked in a space of 2500mm*	M	P	P	M	P	P	P	P	P	M
9	*Sealing*	P	P	I	P	M	P	P	P	Q	Q
10	*Premium feeling (smooth operation)*	P	I	P	M	P	M	A	I	A	A
11	*AB Flange compression direction and engagement*	A	M	I	A	P	M	I	A	P	P
12	*Give unobstructed access to rear load space.*	M	I	I	P	I	P	M	I	M	M
13	*Manual operation*	I	M	P	I	P	I	I	M	I	I

		TOTAL PERFORMACE											
		Numerical format						***Percentage format***					
No.	**Feature**	**M**	**P**	**A**	**I**	**Q**	**R**	**M**	**P**	**A**	**I**	**Q**	**R**
1	*Low vibrations*	2	*7*	0	1	0	0	20%	*70%*	0%	10%	0%	0%
2	*Shut the lines gaps when close*	3	*5*	2	0	0	0	30%	*50%*	20%	0%	0%	0%
3	*Acceptable speed*	3	*5*	0	2	0	0	30%	*50%*	0%	20%	0%	0%
4	*Low noise level*	2	*7*	0	1	0	0	20%	*70%*	0%	10%	0%	0%
5	*Quality finish appearance when closed or open*	*3*	*3*	2	2	0	0	*30%*	*30%*	20%	20%	0%	0%
6	*Stay open on the slope*	*4*	*4*	0	2	0	0	*40%*	*40%*	0%	20%	0%	0%
7	*Easy to open and close*	*5*	4	0	1	0	0	*50%*	40%	0%	10%	0%	0%
8	*The ability to open the Door when parked in a space of 2500mm*	3	*7*	0	0	0	0	30%	*70%*	0%	0%	0%	0%
9	*Sealing*	1	*6*	0	1	2	0	10%	*60%*	0%	10%	20%	0%
10	*Premium feeling (smooth operation)*	2	*3*	*3*	2	0	0	20%	*30%*	*30%*	20%	0%	0%
11	*AB Flange compression direction and engagement*	2	*3*	*3*	2	0	0	20%	*30%*	*30%*	20%	0%	0%
12	*Give unobstructed access to rear load space.*	*4*	2	0	*4*	0	0	*40%*	20%	0%	*40%*	0%	0%
13	*Manual operation*	2	2	0	*6*	0	0	20%	20%	0%	*60%*	0%	0%

The kano model was constructed by conducting a survey among 10 participants to investigate the expectations of customers regarding selected design features. The survey required participants to select a response out of the options; Like (L), Dislike (D), Neutral (N), Expect (E), and Tolerate (T) that best represented how they would feel if the product had or didn't have the selected features. Additionally, they had to rate each feature with options of; must be feature (M), Performance (P), Attractive (A), Indifferent (I), Questionable (Q) and Reverse response (R). The total performance was then calculated to order each feature by importance to the customer.

The result from the survey shows the easy to open and close the door is the must be feature with greatest percentage of choice (50%). The performance features include door open within the range of 2500 mm (70%), low vibration, low noise level (70%), better sealing around the door (70%) and acceptable opening speed (50%). The other attractive features include Quality finish appearance when the door is opened and closed (20%). Regarding the participants choice, the features are taken into consideration at the top priority and are followed in the QFD (Quality Function Display) to meet the engineering requirements.

5. QFD (Quality Function Deployment)

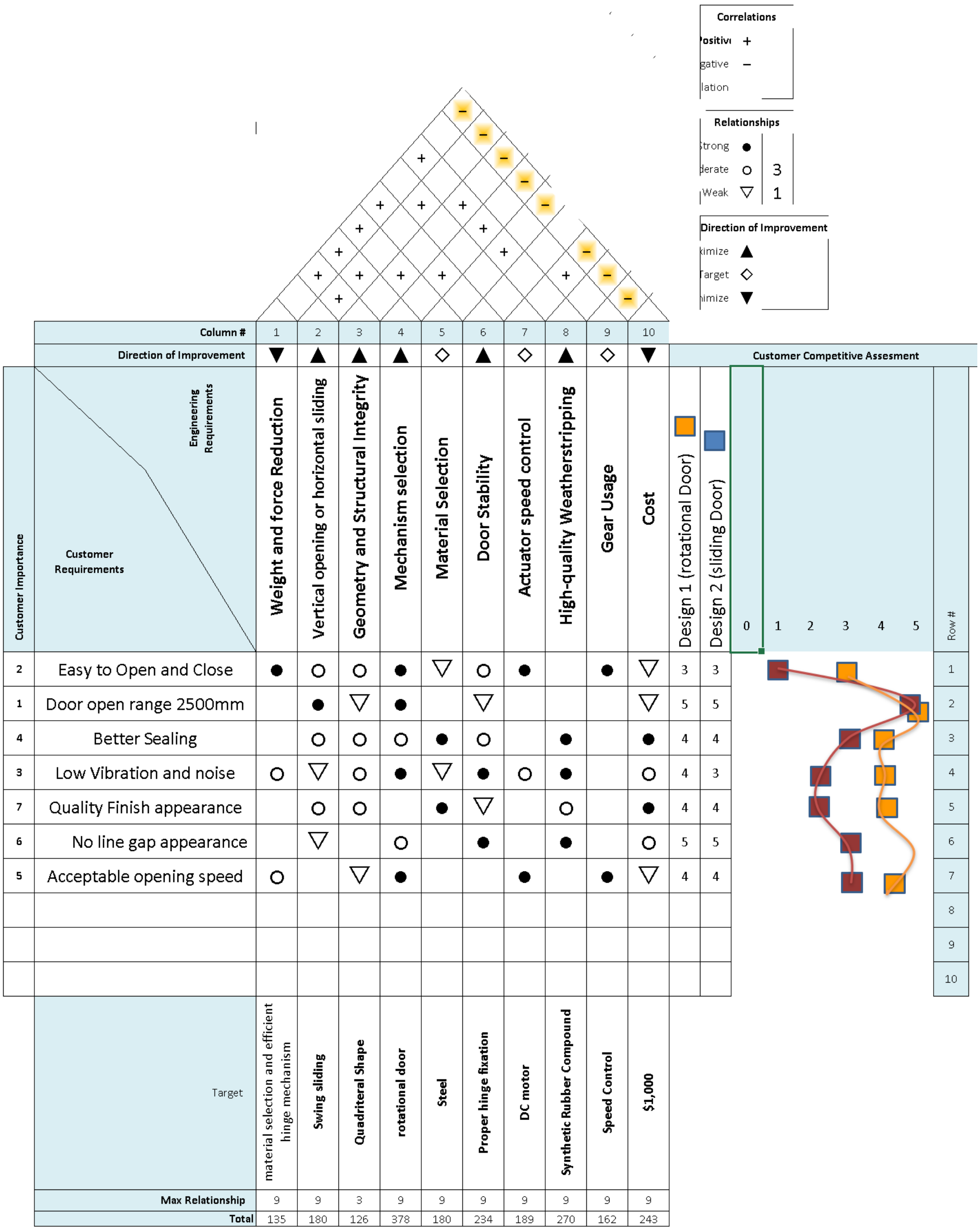


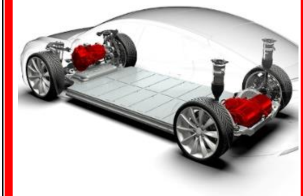
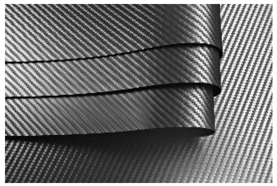
Figure 16: *QFD (Quality Function Deployment).*

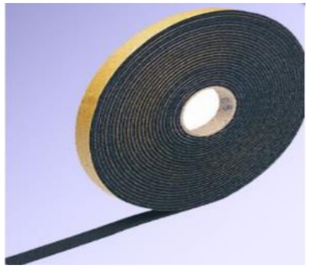
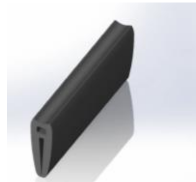
The QFD table is made to meet the customer requirements with the engineering requirements. The engineering approaches like weight and force reduction, mechanism of door opening, material selection, speed control, cost, geometry, and structural integrity are taken into account to fulfil the customer requirements. The relation between all the customer requirements and the engineering requirements are developed and the initial target has been considered. Following this, morphological analysis is developed further to generate and evaluate a wide range of design alternatives to meet final targets of the engineering requirements.

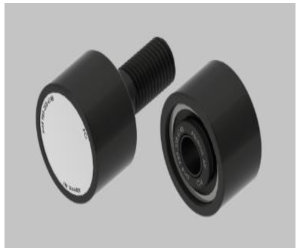
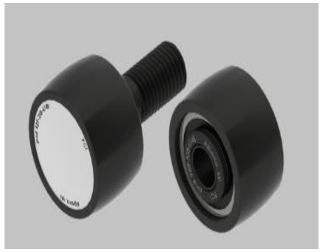
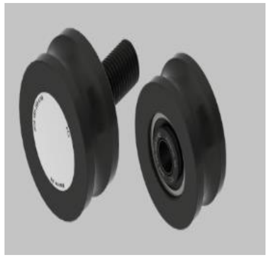
6. Morphological Chart Analysis

Table 2: *Morphological Chart Analysis*

	Option 1	Option 2	Option 3	Option 4	Option 5
General Mechanism	**Hinge**  (Shutterstock, n.d.)	**Roller**  (London., n.d.)	**Hydraulic drive system**  (Hydraulics, n.d.)	**Linear Actuator**  (Amazon, ECO-WORTHY 2pcs 8 Inch Heavy Duty Linear Actuator, n.d.)	**Pneumatic**  (Limited, n.d.)
Hinge Material	**Steel**  (Eclipse, n.d.)	**Aluminium**  (RS, Pinet Aluminium Spring Hinge, Screw Fixing 67mm x 55mm x 4.5mm, n.d.)	**Zinc Alloys**  (SHIN, n.d.)	**Composite Materials**  (DGS, n.d.)	**Brass**  (Station, n.d.)

Power Source	**Alternator.**  (CO., n.d.)	**DC Motor.**  (Components. R. , n.d.)	**Mechanical Energy/Manual Handling**  (Autodeal., Car door handles: Why there are so many different types, n.d.)	**Lithium-ion battery**  (Halfords., n.d.)	**Electric Source**  (Autoevolution., n.d.)
Door Frame Materials	**Aluminium**  (RYERSON, n.d.)	**Plastic**  (PLASTICS.CO.UK, n.d.)	**Steel**  (Store, n.d.)	**Polycarbonate**  (Plastic, n.d.)	**CFRP.**  (SLIPLO, n.d.)

Bearing types	**Ball Bearing**  (RS, SKF Deep Groove Ball Bearing, n.d.)	**Thrust Ball Bearing**  (NSK, n.d.)	**Needle Bearing.**  (RS, SKF HK Needle Roller Bearing, n.d.)	**Sleeve Bearing.**  (RS, SKF 35mm Bore Plain Bearing, n.d.)	**Spherical Roller Bearing.**  (RS, SKF Spherical Roller Bearing, n.d.)
Sealing Material	**Silicone.**  (Amazon, Qishare Silicone Rubber Weather Strip, n.d.)	**Rubber.**  (Autodeal., Car Door Rubber: Maintenance and Replacement, n.d.)	**Neoprene/EPDM foam** 	**PVC.**  (Amazon, Front Door Frame Sealing, n.d.)	**EPDM.**  (Components., n.d.)

Types of track rollers	**Plain Track**  (PCI, n.d.)	**Crowned Track**  (PCI, n.d.)	**Flanged Track**  (PCI, n.d.)	**U-Grooved Track**  (PCI, n.d.)	**Double Flanged Track**  (PCI, n.d.)
Roller Materials	**Nylon**  (Metalines, n.d.)	**Polyurethane**  (Fregot, n.d.)	**Stainless Steel**  (MISUMI, n.d.)	**Aluminium**  (Bearings, n.d.)	**Delrin**  (Edel, n.d.)

Types of Hinges	**Roller Style Hinge**  (UK, n.d.)	**Pivot Hinge**  (Amazon, Pivot Hinge, n.d.)	**Corner Hinge**  (Components, n.d.)	**Offset Hinge**  (Components, n.d.)	**Multiple Joint Hinge**  (Autodoc, n.d.)
Gear Transmission / connection	**Worm Gears.**  (Kelston, n.d.)	**Helical Gears**  (Gears, n.d.)	**Bevel Gears.**  (Sprockets., n.d.)	**Spur Gears**  (Control., n.d.)	**Rack and Pinion Gears.**  (Thomas., n.d.)

The morphological chart has been constructed to display a selection of components, materials, and mechanisms for required aspects of the design. It allows exploration of possible conceptual designs with different configurations. The morphological analysis is used here for the product development breaking down a product to its components and understanding how they function together. In this project, this helps identify design flaws and root cause problems such as limitations to existing products regarding their shape and degrees of freedom. Moreover, it clarifies requirements for materials based on what mechanisms are used. The components selected after the morphological analysis for the final conceptual design has been indicated with a red box.

7. Concept Generation

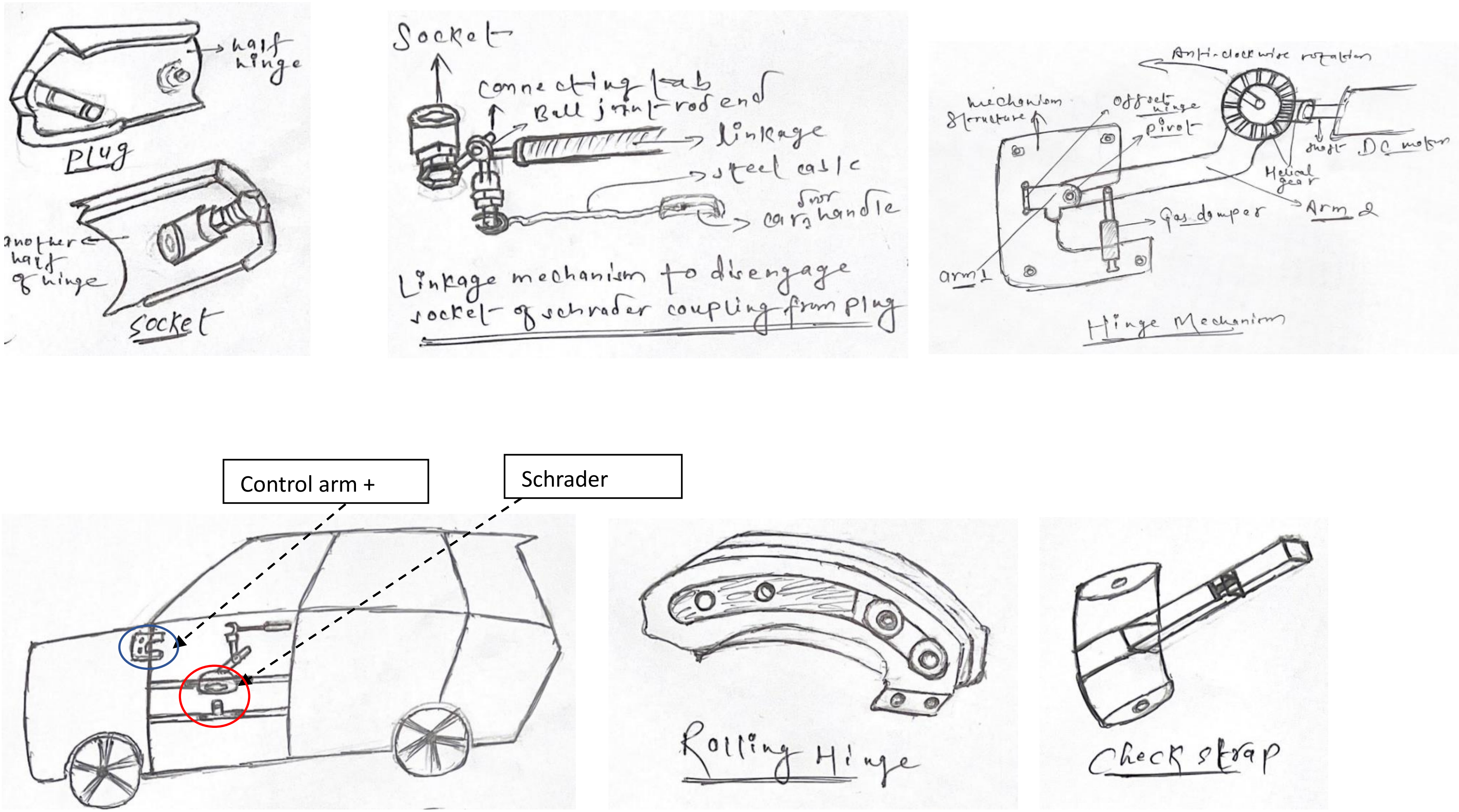


Figure 17: Conceptual designs and mechanism developed for the project.

Concept generation begins with developing a mechanism that allows the door to be operated as two separate parts that fits together. This is accomplished using a Schrader coupling at the middle in-between the doors. A ball joint connects the Schrader coupling to the linkage connected with the door, pulling the door handle pulls the linkage causing the ball joint rod connected with the socket twist together, disengaging the plug of the Schrader coupling as demonstrated in **figure 17**. When the Schrader coupling is disengaged the door will act as two separate parts, where the top half will rotate upwards in the anticlockwise direction by the control arm shown in **figure 17**,whereas the bottom half will slide under the vehicle through the multiple joint hinges on either side of that part of door. The hinge connected with the top half of the door allows lateral movement of the door, a setup of an electric motor and gears will allow the rotation of the car door, a gas spring will then push the door upwards as the control arm rotates about the pivot. The complexity of door sealing and the use of two door operating mechanisms in this design makes it impractical for real world production as it would require unnecessary costs.

Another concept was developed. The door will operate using a sliding mechanism. This works using sliding hinges that have a track and roller embedded within the hinge allowing it to extend and slide the door to the front of the vehicle. A check strap will be used to support the weight of the door and increase stability. Two sliding hinges, one located below the door window and the other at the bottom of the door, will be required to support the full weight of the door.

This is how some of the concepts were generated and further researched and modified to make it practically possible conceptual designs with the consideration of materials, loads, forces and so on.

8. PCC (Pairwise Comparison)

The pairwise comparison Chart is used to compare design objectives and rank them in order of importance. This is done by deciding whether an objective is more important **(1),** or less important **(0)** than another objective going across the rows. **Table 3** shows a pairwise comparison chart for the car door mechanism. This shows that Safety is the most important design objective and noise control, and cost are the least important.

Table 3: *Table showing pairwise comparison.*

Objectives	Cost	Noise control	Durability	Safety	Easy to operate	Total Score
Cost		0	0	0	1	1
Noise control	1		0	0	0	1
Durability	1	1		0	0	2
Safety	1	1	1		1	4
Easy to operate	0	1	1	0		2

9. Conceptual Designs

9.1. Conceptual Design 1

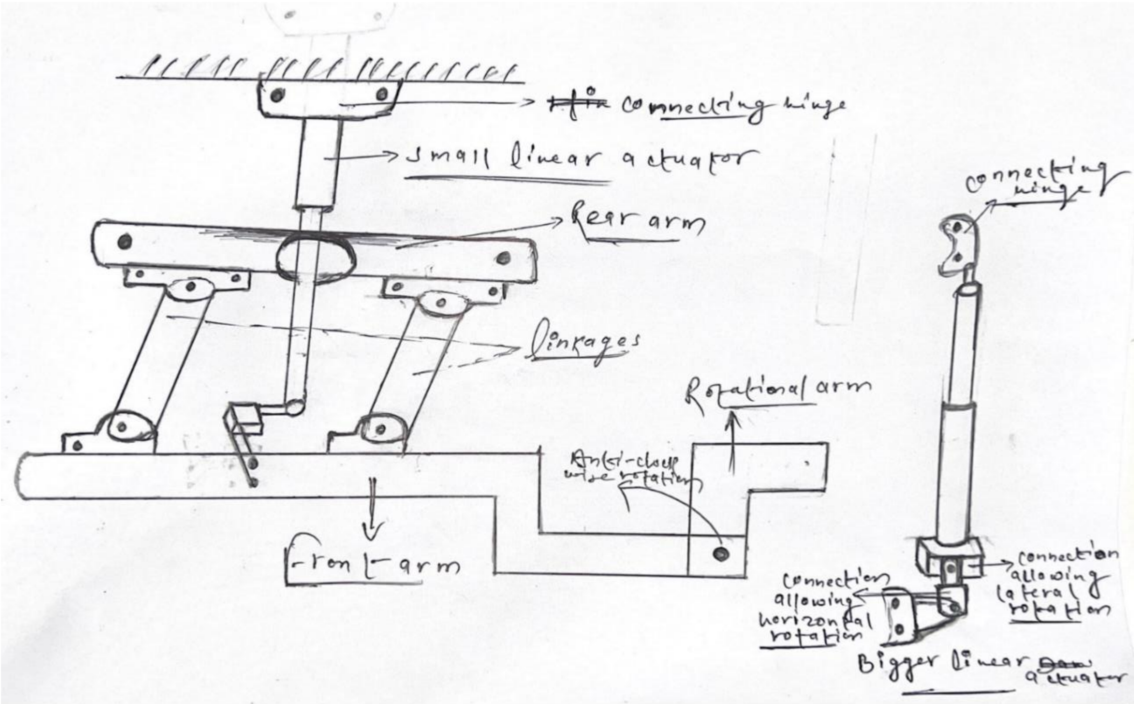
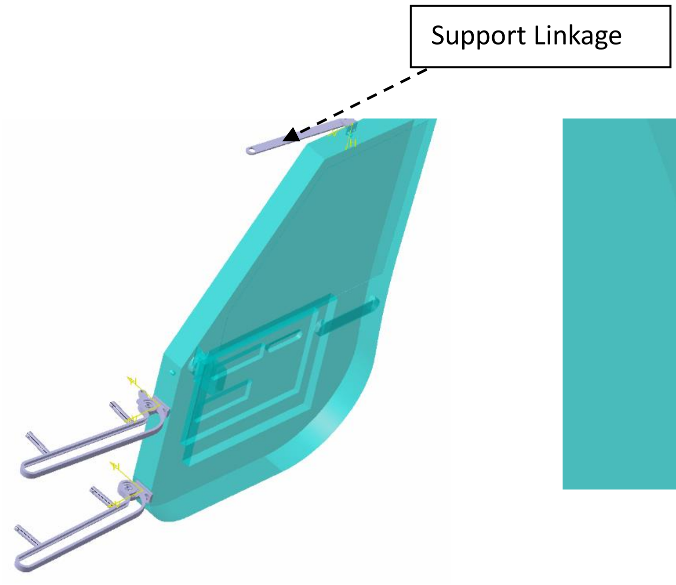


Figure 18: Main conceptual design of the project, showing the hinge parts and its operation.

Hinge Components: The aforementioned picture labels the main features of conceptual design 1. The front arm, rear arm, two linkages, rotational arm, connection hinges, small linear actuator, bigger linear actuator comprise the entire mechanism.

Mechanism: The mechanism is based on the hinge and the linear actuator. The rear arm of the hinge will be connected with the car body and the small linear actuator will also be connected with the car body little farther than the rear arm. The rear arm provides complete support to the hinge due to which small linear actuator don't have to bear the heavy load of the hinge. The car door will be supported and connected with the rotational arm and the rotational arm is aligned and connected to the front arm with the pin support. The linkages connect front arm and the rear arm with the support of connecting hinges. The linkages will be at rest (close to 30˚ angle) during closed state of the door which keeps the front arm of the hinge bit closer to the rear arm. As the small linear actuator extends, the linkages raised up to certain angle (close to 80˚) pushing the front arm laterally outside the car body up to certain distance (130 mm). This will be controlled by the small linear actuator and the door now will be at the half-opened state. The one end of the bigger linear actuator will be connected at the bottom of the fender of the car body and another end will be connected near the front corner of the car door. At the phase of half opened state, the linear actuator will be actuated and extend up to certain length (350 mm) which allows the anti-clockwise rotation of the door from the pivot point of front arm and the rotational arm, causing the door to open. The sleeve bearing connected at the pivot point makes the rotation smooth. The linear actuator remains stiff throughout the process to maintain the door opening and closing. The overall process will be based on electric as and will be key controlled.

9.2. Conceptual Design 2



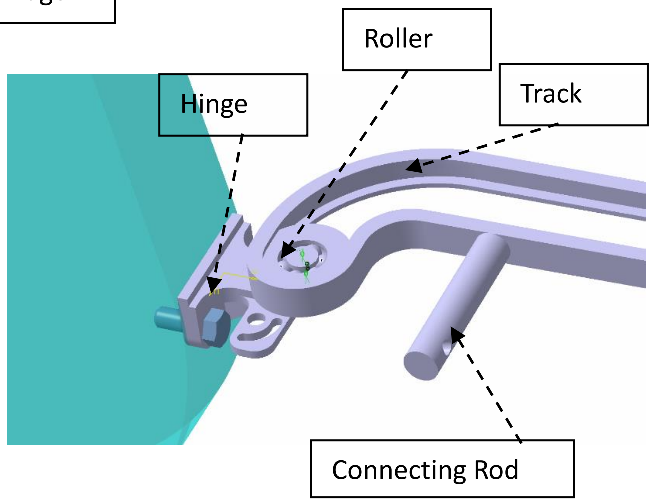


Figure 19:*View of door with connection.*

Figure 20: *Close up view of hinge connection.*

Sliding mechanism componens : Hinge, Roller, Track, Connecting Rod, Support Linkage, Check Strap.

Mechanism: The door will operate using a sliding mechanism. This works using sliding hinges that have a track and roller embedded within the hinge allowing the door to slide open as the roller slides along the track. A check strap will be used to support the weight of the door and increase stability. The check strap will be connected to both the door and car body and will have a bearing at the middle of the strap allowing to move freely so that it doesn't fracture when the door is opened. Two sliding hinges, one located below the door window and the other at the bottom of the door, will be required to support the full weight of the door. The sliding hinge will be connected with the car door by a hinge and the use of screws, this hinge will be connected directly to the roller. The sliding hinge will have two connecting rods which will slip into the car body along the front fender allowing the sliding hinge to be concealed within the vehicle body. A Support Linkage will also be used to provide additional support while the door is open. The support linkage will be connected at the top of the door and at the middle of the A pillar, and will be connected using pins, the connection at the top of the door will be fixed to restrict unwanted movement of the door whereas the connection with the vehicle body the linkage will be able to rotate about the pivot so it can move.

Since the rolling mechanism is noisy, the roller material that will be used in this mechanism is stainless steel to provide the strength and it will be coated with the nylon form outside due to its low coefficient of friction and softness which reduce noise providing smoother and quieter operation during sliding.

10. AHP (Analytical Hierarchy Process)

Criteria	Priority Vector (PV) for Criteria	Sub-Criteria	Priority Vector (PV) for Sub-Criteria
Cost	0.196	Production Cost	0.750
		Maintenance Cost	0.250
Convenience	0.396	Easy to Handle	0.167
		Safe to Operate	0.833
Manufacturability	0.158	Durability	0.648
		Easy Assembly	0.230
		Low part count	0.122
Performance	0.249	Energy Efficiency	0.750
		Speed	0.250

(PV for Criteria) x (PV for Sub-Criteria)	Design A	Design B
0.147	0.332	0.368
0.049	0.333	0.333
0.066	0.539	0.164
0.330	0.589	0.252
0.103	0.524	0.304
0.036	0.298	0.370
0.019	0.298	0.370
0.187	0.512	0.330
0.062	0.578	0.302

	Design A	Design B
	0.0489	0.0541
	0.0163	0.0163
	0.0356	0.0108
	0.1944	0.0832
	0.0537	0.0312
	0.0108	0.0135
	0.0058	0.0072
	0.0958	0.0616
	0.0360	0.0188
SUM	0.4974	0.2967
Ranking	***1***	***2***

Analytical Hierarchy Process (AHP) is used to evaluate and prioritize among two of the conceptual designs based on multiple criteria and sub-criteria. The comparison is done on the basis of numbers 1-9 and the number is allocated according to their importance. The evaluation and comparison process of each criterion of AHP has been shown in **Appendix 4.**

11. Final Design

11.1. Mechanism- Closed State of Door

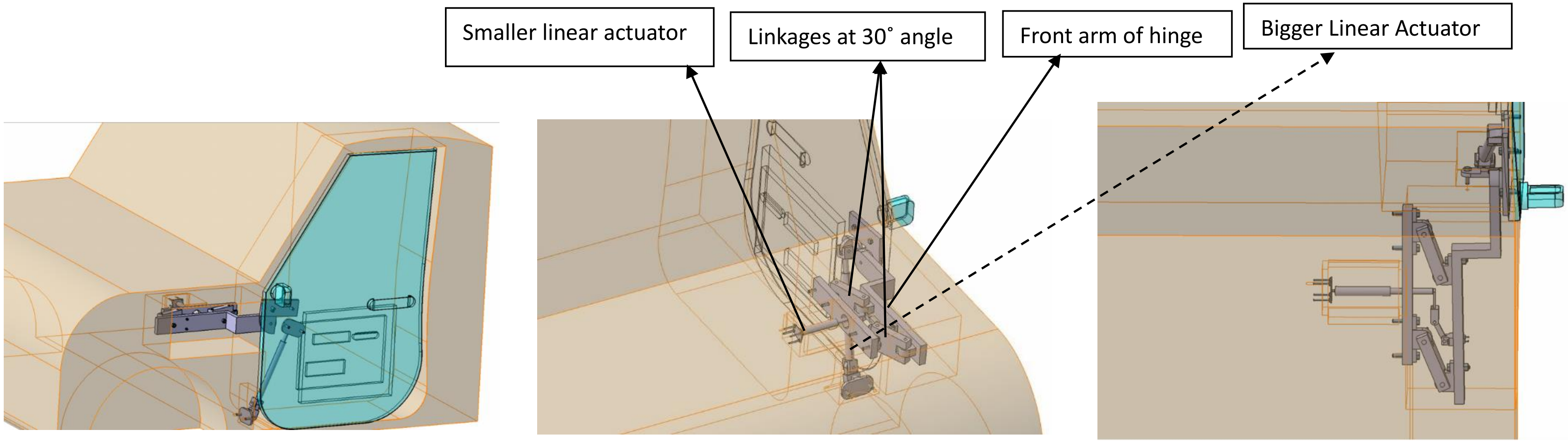


Figure 21: *Door lateral view during closed.* ***Figure 22:****Rear view of the mechanism during closed.* ***Figure 23:*** *Top view of the mechanism closed.*

<u>Mechanism Description</u>: There are two actuators used in this mechanism, smaller linear actuator and the bigger linear actuator as indicated in **fig 22.** When the door is closed, the smaller linear actuator connected with the car body and front arm of the hinge is in a normal state at its original length (no extension of linear actuators). The second linear actuator (bigger one) is also in a normal state and is unable to start extending as the ultrasonic sensors used will prevent the current flow when the door is closed to prevent collisions causing damage. The linkages are at an angle of 30 degrees when the door is closed as demonstrated in **fig 22**. At this angle the vehicle door meets all shut line gaps. An electric motor will be used to engage and disengage the latch, the locking mechanism can be controlled using the car keys or buttons on the interior of the car.

11.2. Mechanism – Half Opened State.

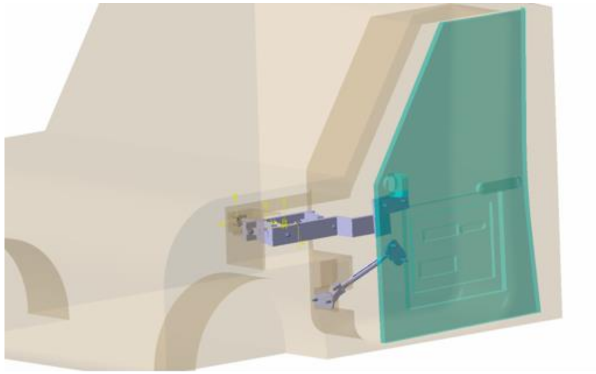


Figure 24: Door lateral view during closed state.

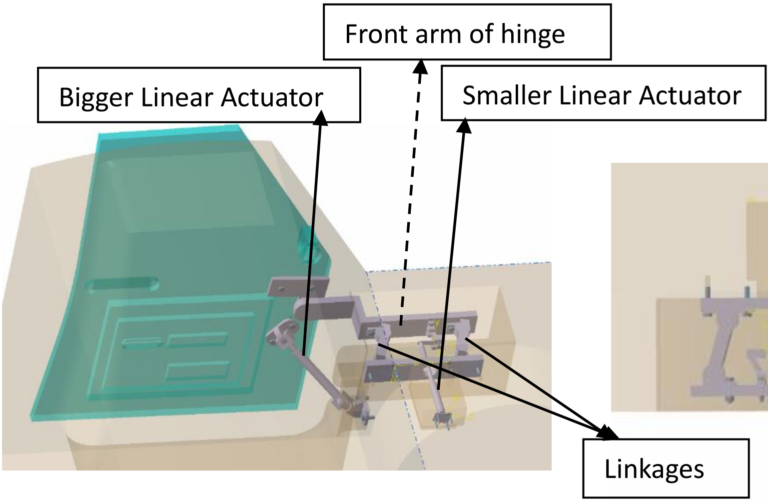


Figure 25: Rear view of the mechanism.

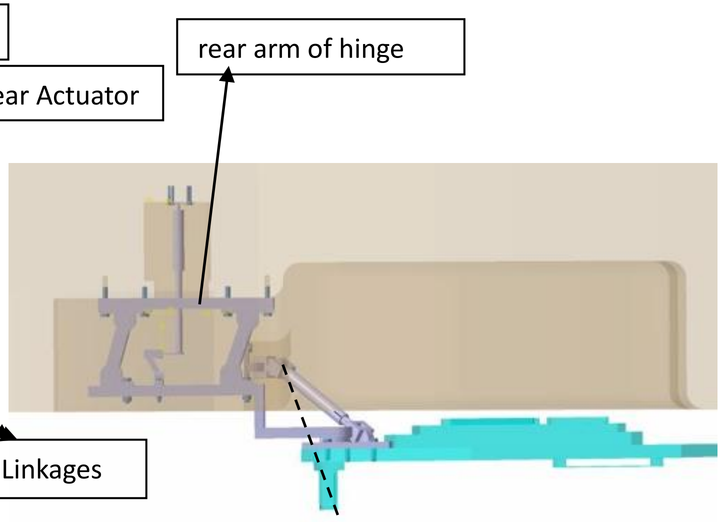


Figure 26: Side view of the mechanism

Mechanism Description: The small linear actuator pushes the front arm of the hinge by **130mm** due to which the linkages will be at **80˚ angle** as can be seen in **fig 26.** At the same time, the **bigger linear actuator** connected at the bottom of the door needs to be shift laterally to avoid the breakage. It is fulfilled by the use of **movement link** installed at the bottom of the linear actuator which allows lateral shifting after the door is pushed by the **smaller liner actuator** as shown in **fig 27.** The larger linear actuator shifts by 130 mm which is the same distance pushed by the smaller linear actuator. Now the position of the door is at 130 mm outward from the closed position of the door which allows a space between the car body and interior of the car door for smooth anti-clockwise opening of the door without collision. Similarly, the linkages maintain the doors at 180˚ angle from the body of the car as shown in **fig 26**. This allows the wider opening of the door as there is no risk of a door-to-bonnet collision. The stability of the front arm of the door is maintained by the smaller linear actuator which acts a check strap in a conventional car door. Similarly, the stability of the door and its control is maintained by the bigger linear actuator. The linkages are restricted to extend beyond 80˚ by the smaller

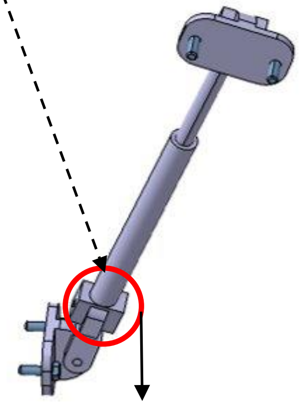


Figure 27: Link for movement.

linear actuator, it is because if the linkages held straight at 90˚, the compressive force applied by the linear actuator while closing the door will be straight to rear arm of the hinge makes it difficult for the linkages get back to 30˚.

11.3. Mechanism – Full Opened State.

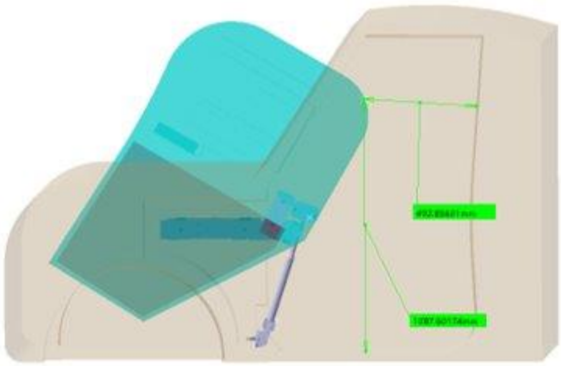


Figure 28: *Mechanism lateral view during full opening.*

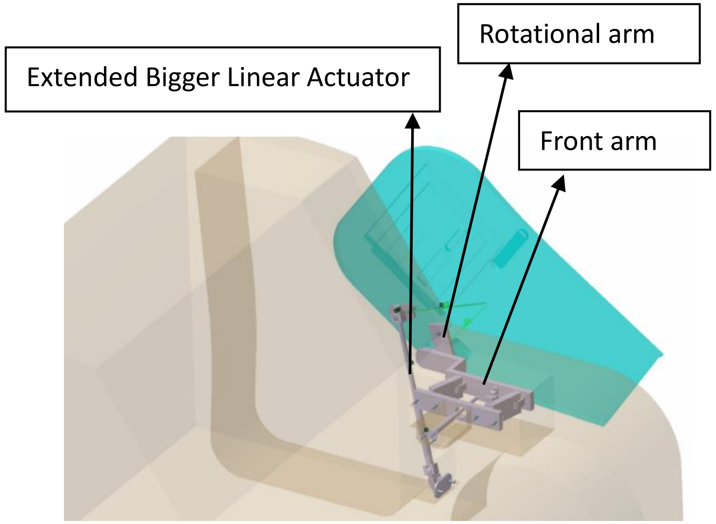


Figure 29: *Rear view of the mechanism.*

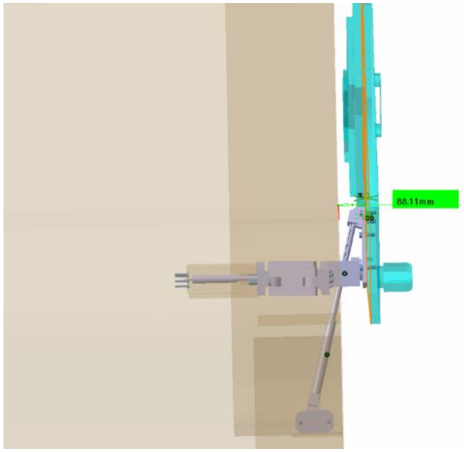


Figure 30: *Top view of mechanism.*

Mechanism Description: After the door is half opened as described above in the half-opened state, the door needs to be pushed upward for its opening. It is fulfilled by the extension of the bigger linear actuator whose one end is connected at the bottom corner of the car body and another end is connected in the door below the window. The bigger linear actuator is extended by **350mm**, causing the door to rotate anticlockwise and open 492.86mm from the rear end of the car body as shown in **fig 29.** As the rotational arm will be connected with the door, the rotation starts from the pivot point between rotation arm and the front arm as can be seen in **fig 29.** In between the pivot point, the sleeve bearing is used for the smooth rotation of the rotational arm. The mechanism is based on the electric system. The linear actuator installed are electric which is connected with the battery of the car and can be controlled using the car key. Ultrasonic and passive infrared sensors are used to prevent linear actuator movement from collisions with nearby people or objects. Similarly, the timing of the actuator to be actuated is controlled applying the control engineering techniques.

11.4. Mechanism- Closing after fully opened

Mechanism Description: The closing mechanism involves similar operation as opening. Instead of extension, the linear actuators will contract for the door closure. The larger linear actuator first contracts and rotates the door clockwise to its half open position. The smaller linear actuator then contracts and rotates the linkage back to a 30 degree angle, closing the door completely. This occurs in a regulated manner while utilising control engineering methodologies.

11.5. Door Opening Speed

The overall objective of door opening is within **8 sec.** Since, the two linear actuators are used, and they are actuated sequentially. The smaller linear actuator was aimed to be completely extended within **3 sec** whereas the bigger linear actuator within **5 sec** to achieve the full opening. The timing is set at average range to reduce any catastrophic failure due to high speed.

Calculation: Power required by the bigger linear actuator to open the door completely within 5 sec.

- $\boldsymbol{maximum\ extension\ of\ linear\ actuator\ (d) = 0.35\ m}$
- $\boldsymbol{required\ time\ (t) = 5\ sec}$
- $\boldsymbol{mass\ of\ the\ door\ (m) = 25\ kg}$
- $\boldsymbol{Force\ (F) = m * g = 245.25\ N}$
- $\boldsymbol{Power\ required\ (P) = ?}$

➢ $\boldsymbol{P = Force\ (F) * velocity(v) \quad where,\ v = \frac{d}{t}}$

➢ $\boldsymbol{P = 17.16\ w}$

Calculation: Power required by the smaller linear actuator to open the door completely within 3 sec.

- $\boldsymbol{maximum\ extension\ of\ linear\ actuator\ (d) = 0.13m}$
- $\boldsymbol{required\ time\ (t) = 3\ sec}$
- $\boldsymbol{mass\ of\ the\ door\ (m) = 25\ kg}$
- $\boldsymbol{Force\ (F) = m * g = 245.25\ N}$
- $\boldsymbol{Power\ required\ (P) = ?}$

➢ $\boldsymbol{P = 10.62\ w}$

Since, the power required by the bigger linear actuator to lift the door/complete opening within **5 sec** is **17.16 watt** whereas the smaller linear actuator to push the front arm of the hinge at the distance of 130 mm within **3 sec** requires **10.62 watt**. Therefore, the linear actuator will be chosen with more than the calculated required power for smooth operation.

11.6. Manual Door Operation

The manual operation of the door is also taken into account which is useful during the low battery condition. For the manual operation, the focus is to calculate the net moment required to open the door. The lesser moment means the less energy required by an individual to lift up the door manually. Firstly, the frictional moment acting at the rotation point is calculated. Secondly, the total moment from the rotation to the perpendicular distance to the handle of the door is calculated. To calculate these moments, the reaction force at the rotation point due to the weight of the door is considered. Finally, the net moment required is found adding the frictional moment and the total moment i.e., **8.13 Nm.** It means, the net moment required to lift the door with hand is low as expected and is easier to apply the calculated amount of moment by female, male or any aged group except kids.

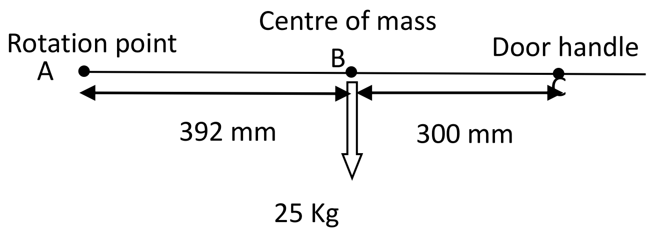


***Figure 31**: Free body diagram of the hinge*

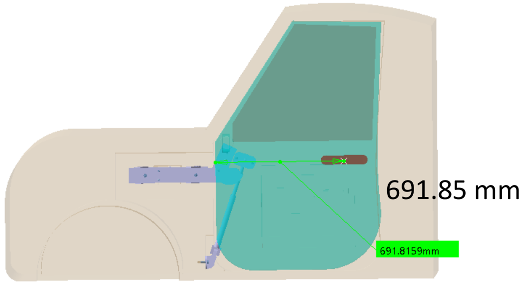


***Figure 32:** Distance between rotation point and hand handle.*

Calculation:

- $\boldsymbol{kinetic\ coefficient\ of\ friction\ of\ low\ carbon\ steel}\ (\mu) = \mathbf{0.2}$
- $\boldsymbol{Perependicular\ distance\ to\ the\ handle\ from\ rotation\ point}\ (\boldsymbol{d}) = \mathbf{692}\ \boldsymbol{mm}$
- $\boldsymbol{Reaction\ force\ at\ rotation\ point}\ (\boldsymbol{F_N}) = \mathbf{25 * 0.392 = 9.8}\ \boldsymbol{N}$
- $\boldsymbol{Frictional\ force\ at\ rotation\ point}\ \left(\boldsymbol{F_f}\right) = \mu * \boldsymbol{F_N} = \mathbf{1.96}\ \boldsymbol{N}$
- $\boldsymbol{Frictional\ moment}\ \left(\boldsymbol{M_f}\right) = \boldsymbol{F_f} * \boldsymbol{d} = \mathbf{1.35}\ \boldsymbol{N}$
- $\boldsymbol{Moment\ without\ friction}\ (\boldsymbol{M}) = \boldsymbol{F_N} * \boldsymbol{d} = \mathbf{6.78}\ \boldsymbol{Nm}$
- $\boldsymbol{Net\ moment\ required}\ (\boldsymbol{M_{net}}) = \mathbf{6.78 + 1.35 = 8.13}\ \boldsymbol{Nm}$

12. Design-Exploded view of crucial components

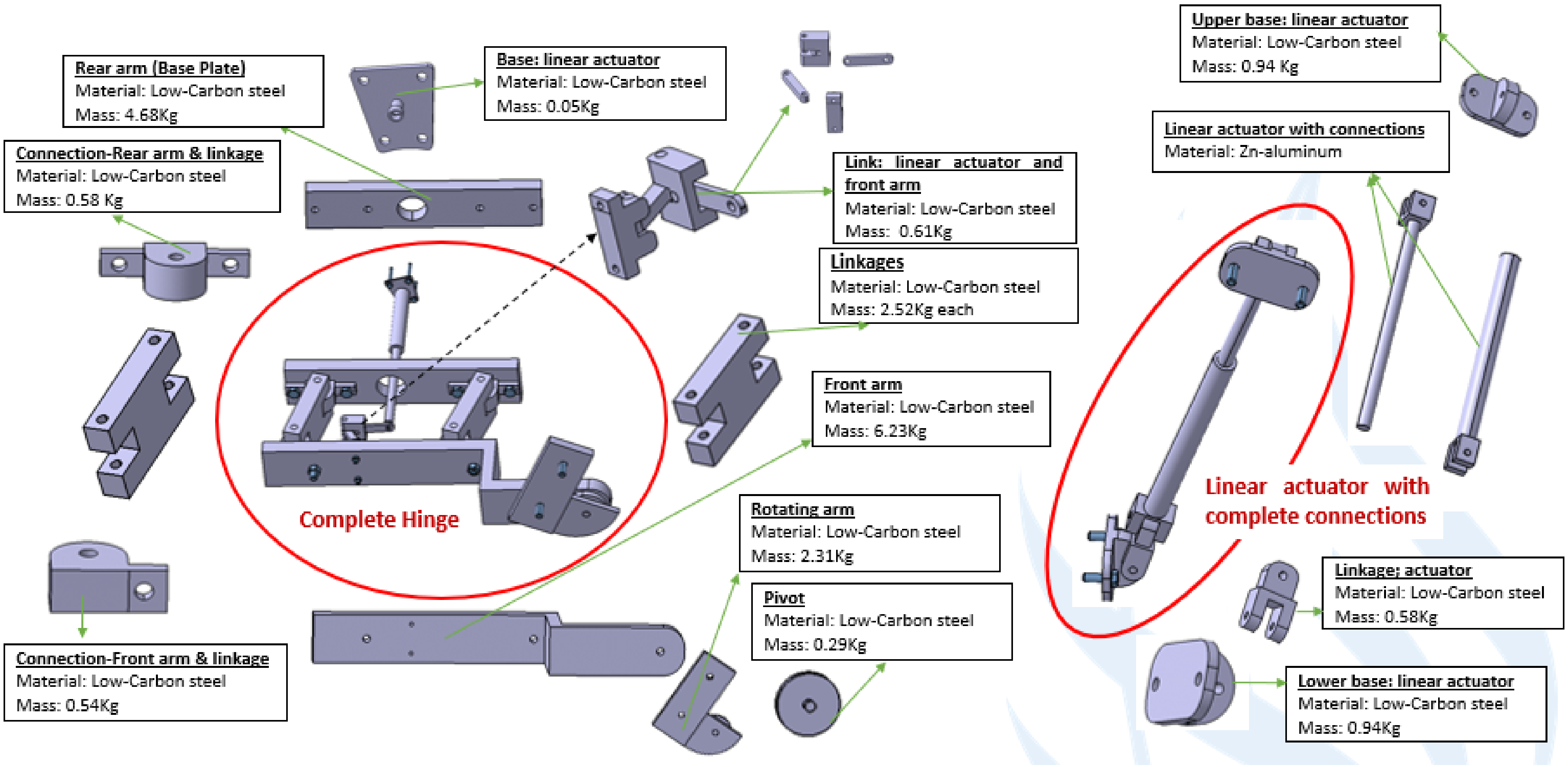


Figure 33:*Design-Exploded View of Crucial components.*

13. DFM (Design for Manufacturing)

Design for manufacturing is the process of designing a component or system while taking manufacturing into consideration from the beginning for the purpose of producing a better product at a lower cost. DFM is essential for the product development process as it results in a final design that is optimised for production. DFM analysis allows to choose the right materials, simplify the design, reduce the number of parts, standardise parts, and design for automation to create a sustainable design. Material selection can have a significant impact on ease of manufacturing and therefore choosing a material that satisfies the design requirements and is easy to manufacture will lower manufacturing costs. Complex design can be expensive and difficult to manufacture so a simplified design will make the manufacturing process more efficient lowering manufacturing costs. Fewer parts result in fewer assembly steps reducing time and cost of manufacturing. Enhancing the use of inexpensive, readily accessible components such as M10 head cap and M6 cheese head will help keep manufacturing costs to a minimum. Designing products while considering automation can help reduce the need for manual labour increasing efficiency of the design.

A major component of DFM is manufacturing cost analysis which is carried out in order to calculate the manufacturing costs (M_i) for each individual component and the whole product by summing the material cost (M_c) and relative and basic processing cost (R_cP_c). This can be calculated using the following formula,

- $M_i = M_c \times R_cP_c$
- $M_c = V_f \times C_{mt} \times W_c$
- $R_c = C_{mp} \times C_c \times C_s \times C_{ft}$
- $R_cP_c = R_c \times P_c$

where,

- V_f = final component volume
- C_{mt} = material cost per unit volume in required form
- W_c = waste coefficient
- C_{mp} = cost associated with material-process suitability
- C_c = cost associated with geometrical complexity
- C_s = cost associated with size considerations
- C_{ft} = max {cost Ct associated with tolerance, cost Cf associated with surface finish}
- P_c = cost for an ideal design of component for a specific process (Swift et al., 2003)

Table 4:*DFM table showing the manufacturing cost of the hinge*.

PRODUCT NAME Hinge

PRODUCT CODE / ID HNX-254

PRODUCT QUANTITY 1,000,000

COMPONENT DETAILS					$M_c = V \times C_{mt} \times Wc$			A		$R_c = C_{mp} \times C_c \times C_s \times C_{ft}$									B	A + B
PART No. ID	PART DESCRIPTION	MATERIAL	PRIMARY PROCESS	SHAPE COMP.	VOLUME V [mm^3]	C_{mt}	W_c	M_C	P_C	C_{mp}	C_c	C_s	Tolerance [mm]	C_t	Surface Finish [µm]	C_f	C_{ft}	R_C	$(P_C \times R_C)$	M_i
1	Eco Worthy 12 V Linear Actuator	Zn-Al alloy	AM	A1	278978.248	0.0005	1.6	221.397	1.3	4	1	1	0.12	1.34	0.4	2.3	2.3	9.2	11.96	233.357
2	M12x40 steel grade C hexagon head screw	stainless steel	AM	A2	6616.976	0.00183	2	24.2181	1.3	4	1.2	1	0.06	1.15	0.8	1.5	1.5	7.2	9.36	33.5781
3	M6x40 steel grade A hexagon head screw	stainless steel	AM	A2	1414.548	0.00183	2	5.17725	1.3	4	1.2	1	0.06	1.15	0.8	1.5	1.5	7.2	9.36	14.5372
4	M12x50 steel grade A hexagon head bolt	stainless steel	AM	A2	8684.573	0.0018	2	31.2645	1.3	4	1.2	1	0.06	1.15	0.8	1.5	1.5	7.2	9.36	40.6245
5	M6x50 steel grade A hexagon head bolt	stainless steel	AM	A2	1727.174	0.0018	2	6.21783	1.3	4	1.2	1	0.06	1.15	0.8	1.5	1.5	7.2	9.36	15.5778
6	Door Hinge	low-carbon steel	IC	A2	145953.8055	0.00044	1	64.2197	11.2	1	1.2	1.5	0.06	2.1	0.6	1.8	2.1	3.78	42.336	106.556
7	Linkages	low-carbon steel	IC	A1	49730.34295	0.0004	1	19.8921	11.2	1	1	1.5	0.08	1.8	0.4	1.6	1.8	2.7	30.24	50.1321
8	M6 steel grade A hexagon nut	stainless steel	AM	A2	349.263	0.00183	2	1.2783	1.3	4	1.2	1	0.06	1.15	0.8	1.5	1.5	7.2	9.36	10.6383
9	M12 steel grade A hexagon nut	stainless steel	AM	A2	2150.733	0.00183	2	7.87168	1.3	4	1.2	1	0.06	1.15	0.8	1.5	1.5	7.2	9.36	17.2317
10	M12x60 steel grade C hexagon head screw	stainless steel	AM	A2	8796.841	0.00183	2	32.1964	1.3	4	1.2	1	0.06	1.15	0.8	1.5	1.5	7.2	9.36	41.5564
																			Total Cost (p)	563.789

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A component manufacturing cost matrix was produced using the manufacturing cost analysis as shown in **Table 5.** The total manufacturing cost for the whole product was **563.79 pence.** The cost of the standardised parts such as the M6x40 steel grade A hexagon head screw were the lowest as they have a much lower volume thus having a lower material cost.

14. Material selection

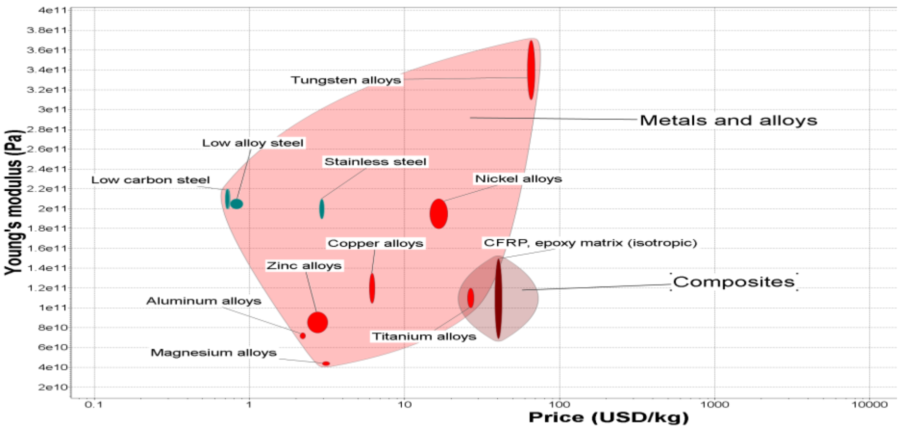

Figure 34:** Young's modulus and Price graph of various metals* ***(GRANTA EDUPACK)

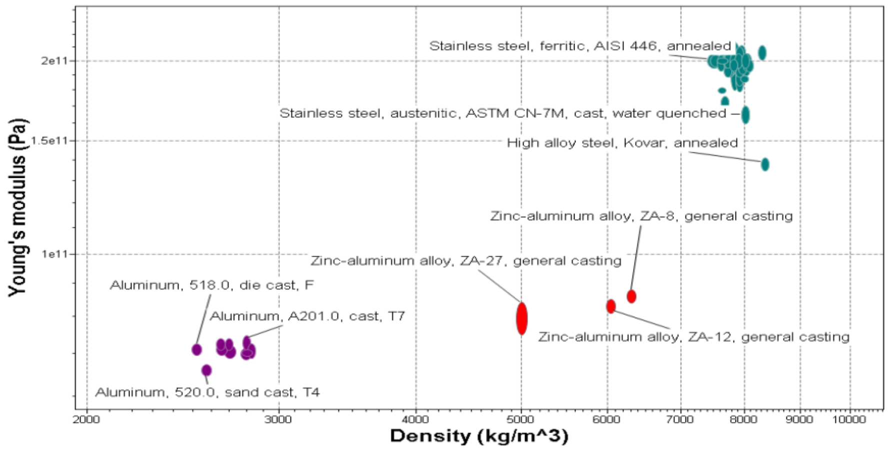

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Figure 35:** Yield Strength Vs Density of various metals.* ***(GRANTA EDUPACK)

For the **hinge** and the **arm** connecting the hinge AISI 1025 carbon steel (0.25% C) was chosen(Low carbon steel grade). Low carbon steel (0.68-0.73 Kg/USD) is cheaper than other suitable materials such as high carbon steel (0.71 – 0.75 Kg/USD) and Aluminium alloys (2.12 – 2.29 kg/USD) while still having sufficient yield strength (255 MPA- 355 MPa) and the tensile strength (3.79 MPa – 532 MPa) to resist stresses while in use. It is also easier to cut, form and weld than other suitable materials due to the less carbon present in it. A 0.25% plain carbon low carbon steel alloy was chosen as the presence of less carbon makes it more feasible from the stress cracks caused by temperature changes and pressure. It also produces an oxide layer on its surface, preventing further oxidation and corrosion of the underlying metal. The ductility makes it more resilient to fatigue failure and bending. It has the fatigue strength at 10^7 cycles are nearly 250 MPa These components will be manufactured using investment casting. Investment casting although more expensive than other manufacturing processes such as stamping, it allows production of complex shape products and importantly better surface finish whereas stamping is mainly used for simple shapes. **(GRANTA EDUPACK)**

The Linear Actuator chosen will be made from a ZA-27 Zinc-Aluminium alloy. Firstly, this grade of Zn-al alloy consists of 25% aluminium, 69% Zn. Zinc-Aluminium alloys have yield strength (235 – 395

MPa) and high tensile (290 – 445 MPa) making it strong enough to withstand the stress experienced by the linear actuator during dynamic movement of opening and closing the door. Similarly, it can act like a hinge support during door closure. Additionally, Zinc-Aluminium alloys are corrosion resistant (400˚C - 500˚C) and non-sparking resulting in reduced risks and increased longevity. Furthermore, the low melting point (375 – 492 ˚C) of Zinc-Aluminium alloys make them easy to manufacture and machining as they are more energy efficient therefore making them cheaper to manufacture than steel alloys of similar strength. Although it has some disadvantages over metals like pure aluminium such as higher density (4.95e3 kg) which is almost two times of its weight but still 2 times smaller than stainless steels and carbon-steels. Moreover, it has higher yield strength and tensile strength in comparison with the pure aluminium which is required according to its use in the rotating door and can be available in very similar price of aluminium (2.34 -2.67 USD/Kg). **(GRANTA EDUPACK).**

The materials for screws, nuts and bolts are chosen as stainless steel due to the requirement of high strength to hold the hinges at each connection without failure. The stainless steel has high yield strength (257 – 1.14*10^3 MPa) and strength to weight ratio 26 – 62. Similarly, the tensile strength (515 – 1.3*10^3 MPa) of the stainless steel is even higher in comparison to the materials like aluminium and may be similar to carbon-fibre but it is more ductile (5.76e7) while carbon fibre is brittle in comparison (6.12e6). It is highly corrosion resistance and is resistant to wear and tear which makes it durable. Stainless steel is a versatile material for a variety of applications, from small components to large structures as it can be fabricated into a wide range of shapes and sizes. It might be bit costly (2.82 – 3.02 USD/Kg) but the use of the stainless steel material in small components like nuts, bolts, and screws won't significantly raise the cost. Therefore, it is cost-effective for the specific purpose mentioned.**(GRANTA EDUPACK).**

Neoprene/EPDM composite foam strips were selected for the weatherstrips to seal the vehicle door. The composite passes 3c08 requirements but the majority polymer is EPDM. This was selected because Neoprene provides high resistance against oils, alkalis and acids additionally the EPDM has good weathering, heat and ozone resistance. The composite has a peel adhesion of 1100N/m to steel for a temperature range of -10°C to 60°C making it a suitable material as weather strips will not experience a force greater than this and will not be stored at a temperature that exceeds this range therefore limiting the chances of the seal peeling off and increasing its reliability.

Specification	Test Method	Required Limits	Test Results
Compression @25% Deflection (kPa)	ASTM D1056-00	35 – 65	43
Compression @50% Deflection (kPa)	ASTM D1056-00	80 – 160	112
Compression Set @50% 22h 20°C (kPa)	ASTM D1056-00	25% Max	19.1%
Water Absorption, max. change in weight (%)	ASTM D1056-00	10	0.8
Heat Aging, Change in Compression, 168h @ 70°C		±30%	Pass
Density (kg/M³)	ISO 845-95	120 ± 20	122
Flammability	FMVSS 302	Burn Rate < 100mm	Pass
Flammability	UL94 HBF		Pass
Elongation at Break (%)	ISO 1798-7		>180
Tensile Strength (KN/M²)	ISO 1798-7		>500
Temperature Range (°C)			-40°C to 85°C
High Intermittent			+100°C
Resistance to Air + UV			Excellent
Resistance to Oil			Poor
Resistance to Acids			Good
Environmental Protection			CFC and HFC free / Fully Recycleable
Specification		ASTM D1056-00 AFNOR 99-211	2A2 B2C 2C08/3C08 B3 C2

Figure 36:*Figure showing specification of composite Neoprene/EPDM. (POLYMAX,n.d)*

15. DFA

Design for Assembly (DFA) is a methodology used to optimise a design for ease of assembly. It aims to increase efficiency and reduce the cost to assemble the product. This is achieved by breaking down the assembly into subcomponents, analysing the assembly process, identifying and eliminating unnecessary steps, minimizing number of parts, simplifying the design and reducing the need for use of specialised tools during assembly.

- The total cost is calculated using the equation, $C_{MA} = C_l (F + H)$ where,
- C_l = labour rate
- F = component fitting index
- H = component handling index

Equation for the component fitting index (F):

- $F = A_f + [\sum_{i=1}^{n} Pf_i + \sum_{i=1}^{n} Pa_i]$ where,
- A_f = basic fitting index for an ideal design using a given assembly process
- P_a = penalty for additional assembly processes on parts in place
- P_f = insertion penalty for the component design

- Equation for the component handling index (H):
  $H = A_h + [\sum_{i=1}^{n} Po_i + \sum_{i=1}^{n} Pg_i]$ where,
- A_h = basic handling index for an ideal design using a given handling process
- P_o = orientation penalty for the component design
- P_g = general handling property penalty (Swift et al., 2003)

Table 5: *DFA table showing the Assembly cost of the hinge.*

PRODUCT NAME Hinge

PRODUCT CODE / ID HNX-255

Labour Rate Cl 0.31 p/s

COMPONENT DETAILS			Handling Index H = Ah + [∑Po + ∑Pg]					H	Fitting Index F = Af + [∑Pf + ∑Pa]									F	Line Total (F + H)	$C_l(F + H)$ C_{MA} (cost in pence)
PART No. ID	PART DESCRIPTION	ASSY PROCESS	Ah	P_{O1}	P_{O2}	$\sum P_O$	$\sum Pg$		Af	Pf_1	Pf_2	Pf_3	Pf_4	Pf_5	Pf_6	$\sum Pf$	$\sum Pa$			
1	Eco Worthy 12 V Linear Actuator	HAND/FIT	1.5	0.1	0.1	0.2	0	1.7	1	0	0.7	0	0	0	0	0.7	0	1.7	3.4	1.05
2	M12x40 steel grade C hexagon head screw	HAND/FIT	1.5	0.1	0	0.1	0	1.6	4	0	0	0	0	0	0.1	0.1	0	4.1	5.7	1.77
3	M6x40 steel grade A hexagon head screw	HAND/FIT	1.5	0.1	0	0.1	0	1.6	4	0	0	0	0	0	0.1	0.1	0	4.1	5.7	1.77
4	M12x50 steel grade A hexagon head bolt	HAND/FIT	1.5	0.1	0	0.1	0	1.6	4	0	0	0	0	0	0.1	0.1	0	4.1	5.7	1.77
5	Door Hinge	HAND/FIT	1.5	0.1	0.1	0.2	0	1.7	1	0	0.7	0	0	0	0	0.7	0	1.7	3.4	1.05
6	Linkages	HAND/FIT	1.5	0.1	0.1	0.2	0	1.7	1	0	0	0	0	0	0	0	0	1	2.7	0.84
7	M12 steel grade A hexagon nut	HAND/FIT	1.5	0.1	0	0.1	0	1.6	4	0	0	0	0	0	0.1	0.1	0	4.1	5.7	1.77
8	M12x60 steel grade C hexagon head screw	HAND/FIT	1.5	0.1	0	0.1	0	1.6	4	0	0	0	0	0	0.1	0.1	0	4.1	5.7	1.77
9	M6x50 steel grade A hexagon head bolt	HAND/FIT	1.5	0.1	0	0.1	0	1.6	4	0	0	0	0	0	0.1	0.1	0	4.1	5.7	1.77
10	M6 steel grade A hexagon nut	HAND/FIT	1.5	0.1	0	0.1	0	1.6	4	0	0	0	0	0	0.1	0.1	0	4.1	5.7	1.77
																		Total Time	49.4	Total Assy Cost 15.31

The component assembly costing matrix was produced as shown in **Table 6.** The total cost of manual assembly (C_{MA}) is 15.31 pence. The off the shelf fixing components such as M12x40 steel grade C hexagon head screw were the most expensive components to assemble with a cost of manual labour of 1.77 pence. This is due to the fact that they have a fitting index (A_f) of 4 (for smaller components) while all other components have a fitting index of 1, this difference makes them more expensive for assembly.

Both DFM and DFA share the approach of reducing the part count as they lessen the overall manufacturing and assembly work needed for the entire component. The component created as a result of the decreased part count, however, could have a more expensive manufacturing cost if it has a complex geometry. Therefore, the design of hinge is tried to be made simple with the less components possible i.e., (two arms connected with a pin and screws). Despite the fact that Screw, nut and bolt components are less expensive, installing them requires more labour. The quantity of fasteners used during design should be maintained to a minimum to minimise the cost of assembly. Other fasteners that need assembly procedures with low fitting indices, like insertion, snap fit, and rivets, could be utilised in place of screws if works.

To reduce the assembly cost of the hinge design, the reorienting parts were avoided or minimised. The symmetricity is maximized in most of the parts like in between linkage connection, hinge connections. One hand easy handling part have been used except the screws and bolts. The base assemblies (such as hinge base and actuator base) are made rigid and large which reduce complexity in assembly. Rather than designing and manufacturing screws and nuts, the standard nuts, bolts and screws has been used which saves manufacturing cost and assembly time. The fragile, flexible, or abrasive parts has been avoided.

15.1. Assembly Structure Diagram

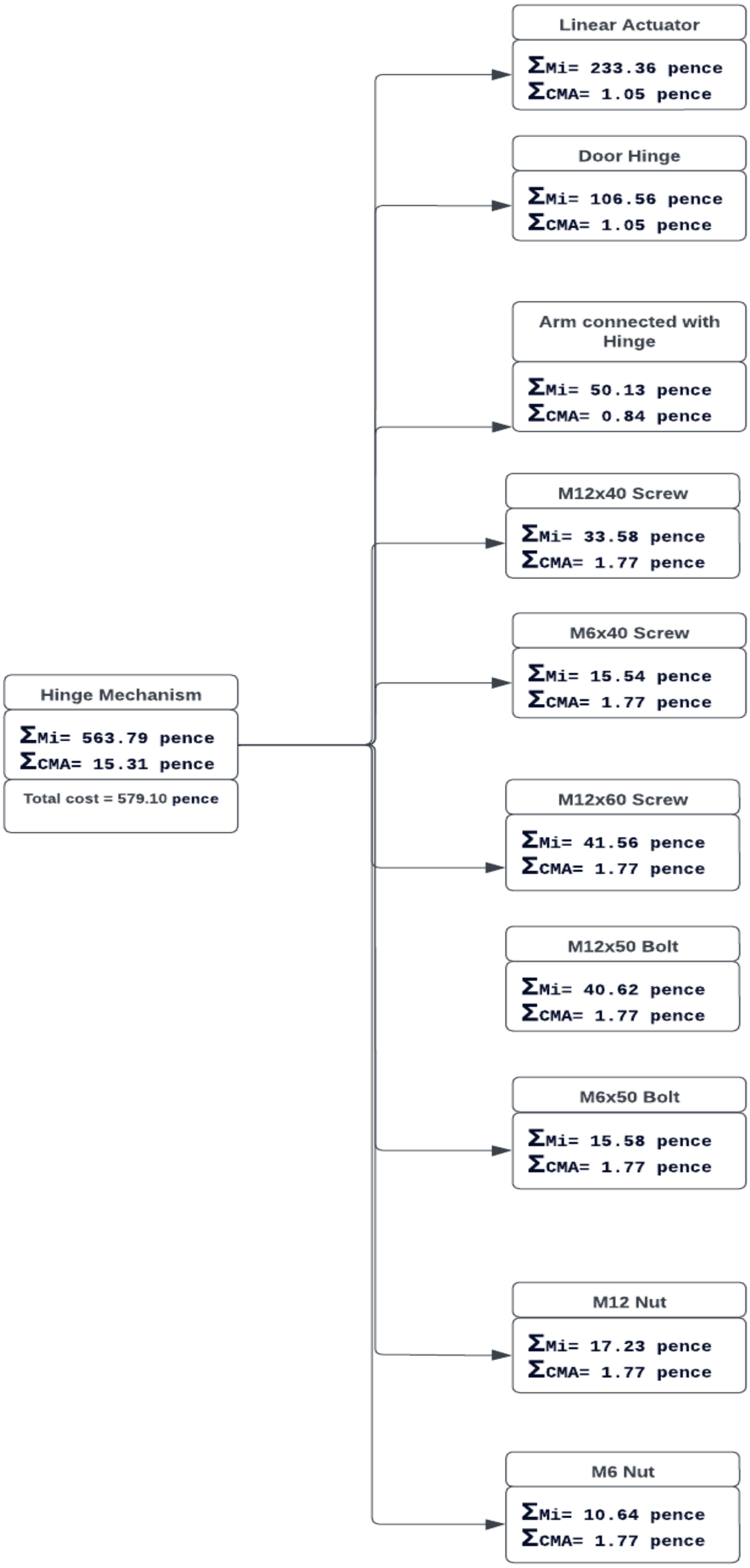


Figure 37: *Assembly Structure Diagram.*

16. Costing

The required power to lift the door up was calculated to be **17.16 W** therefore a linear actuator with a motor with a rated power of at least **34.32 W (2 x required power)** would be a suitable for the bigger linear actuator. Additionally, the linear actuator should be able to extend by at least 350mm as this is the required extension to open the door. The smaller linear actuator connected with the hinge should be able to extend by 130mm at least as this is the required extension. Considering these requirements linear actuators with a maximum power of **36 W** was selected in varying sizes of 6-inches and 14 inches. Neoprene/EPDM foam strips will be used for the sealing.

Linear Actuators:

(Amazon E. w., n.d.)

Eco worthy Linear Actuator 6-inch- £63.99

https://www.amazon.co.uk/ECO-WORTHY-Actuator-Wireless-Controller-Industry/dp/B0191ICF86?th=1

Eco worthy Linear Actuator 14inch-71.99

https://www.amazon.co.uk/ECO-WORTHY-Actuator-Wireless-Controller-Industry/dp/B0191ICF86?th=1

Neoprene/EPDM foam strips:

Price: £16.25

Roll length- 10m

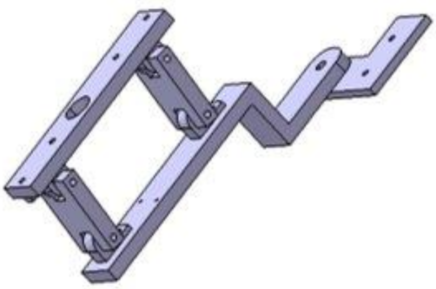
Thickness: 25mm

Width: 25mm

Source: https://www.polymax.co.uk/rubber-sheet/sponge-epdm-neoprene-foam-strips-sah

The hinge component excluding screw, nuts and bolts will be £18.96, this was calculated by summing the material cost , manufacturing cost (DFM), Assembly cost (DFA).

Designed Hinge:



Cost of AISI 1025 c steel: 5.1e3 GBP/m^3 = £5100/m^3

Cost of manufacturing = 156.66 pence

Cost of assembly = 15.31 pence

Table 6: *Screw, Nuts and Bolts quantity and cost.*

Component	Price	Quantity
M12x40 steel grade C hexagon head screw	£2.20	4
M12x60 steel grade C hexagon head screw	£1.06	4
M6x40 steel grade A hexagon head screw	£1.65	4
M12x50 steel grade A hexagon head bolt	£1.53	2
M12x50 steel grade A hexagon head bolt	£2.86	2
M12 steel grade A hexagon nut	£1.15	2
M6 steel grade A hexagon nut	£0.61	2

The total cost of the design including all components used for the mechanism is **£199.47**, this was calculated by summing the cost to manufacture and assemble the hinge along with all off the shelf components.

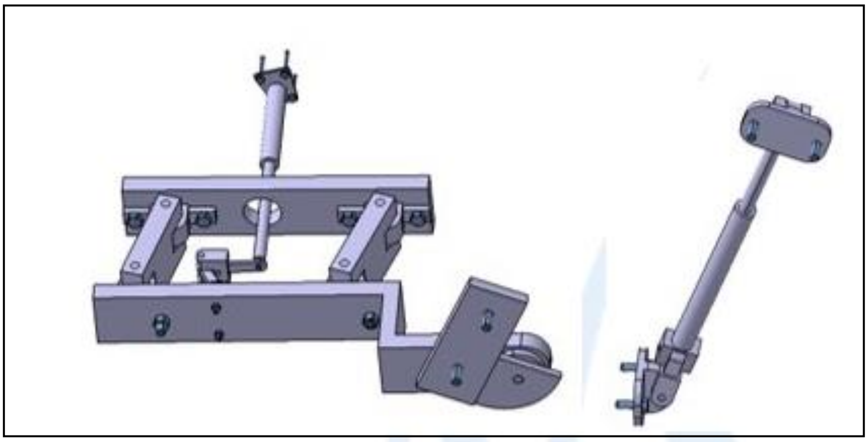


Figure 38: *Shows the complete mechanics of the hinge.*

17. Sustainability

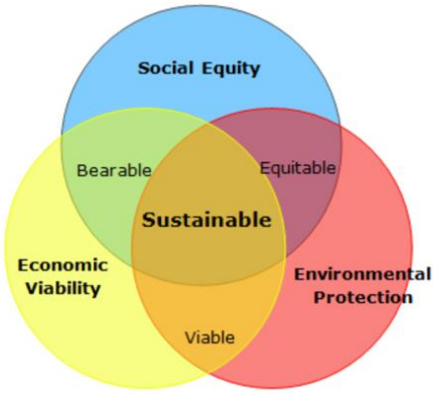


***Figure 39**:Three Pillar of Sustainability*

The three main components of the sustainability include the economic, environmental, and social aspects. Considering all these aspects, the design process of the hinge emphasizes on the availability of resources, life cycle of material, manufacturing process, manufacturing cost and transportation.

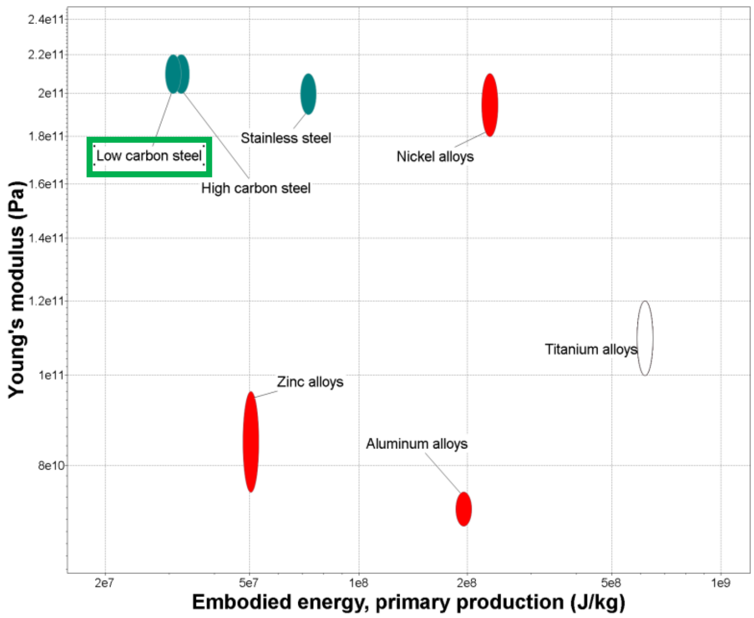


Figure 40:** Graph showing energy needed for the primary production of certain metals.* ***[GRANTA EDUPACK]

Almost all the parts of the hinge materials are taken as a low carbon steel for the design as steel is widely available material which can be easily accessible anywhere. This saves the energy and fuel for the shipping and any transportation cost required to access it. The steel is highly recyclable, durable, energy efficient and versatile material as it has potentially never ending lifecycle and can be 100% recycled without the loss of its quality and strength and is non-toxic. Steel is highly durable and can withstand harsh weather condition, resist corrosion, and maintain strength overtime. This allows steel components to have a long lifespan requiring less maintenance and replacement thus less resources are required for production and disposal. Steel can be produced using hydrogen-based steel making processes and an electric furnace reducing the carbon footprint for steel production. Additionally, it takes less energy to recycle steel than to produce it from raw materials.

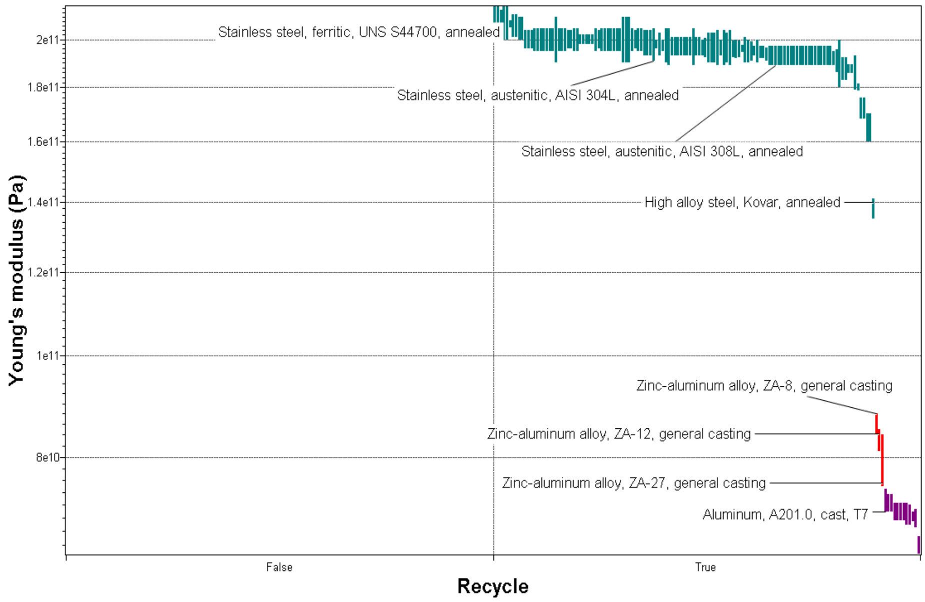


Figure 41: *Graph showing recyclability and young's modulus of zinc alloy and steel.* ***[GRANTA EDUPACK]***

Zinc alloys are highly recyclable and have low toxicity reducing environmental waste. Additionally, they are reliable and durable with a lifespan of up to 100 years, requiring minimal maintenance reducing resources used after manufacturing. Furthermore, the use of zinc alloys is more sustainable than aluminium alloys due to the energy intensive processes required to extract and produce aluminium. **Fig 37** shows the recyclability and the strength of the zinc alloys.

The manufacturing process such as investment casting are emphasized due to its requirement of low temperature resulting in low energy consumption and reduced carbon emission. Investment casting components are frequently used in high-performance situations where durability is crucial, resulting in a longer product lifespan and less frequent product replacement.

The biodegradable polymer such as EPDM has been considered for sealing and the composite of Neoprene has been added to increase its strength for the longer use of it.

Overall, using locally available resources and raw materials, focusing on durability and strength of the component results in financial profit which is one of the major concern of the design. Similarly, the use of locally available materials such as steel fulfils social sustainability as the raw material extraction, processing, and transportation can result in the creation of employment and economic opportunities for local residents.

The design of mechanism focused on the use of the available raw materials, manufacturing process, the length of use, transportation, and the end-of-life. After the end-of-life, it forms a closed loop of becoming the raw material which is less lot wasteful and less polluting. The design was tried to be completed with as less part as possible to reduce the production which contribute to use less resources contributing to minimal waste. Eventually, the overall sustainability process considered for the hinge design process is focused on financial profit, environment conservation and social equity.

18. FEA of Hinge, modal validation (Hand Calc.) and optimization

18.1. Finite Element Analysis of Hinge

A FEA **static analysis** of the Hinge was carried out in the software, Hyperworks. The CAD file of the Hinge was imported and the following considerations were made to carryout the Finite Element Analysis.

- Material: Low Carbon Steel. (specified in the material selection)
- Youngn's Modulus: 220000 MPa. (extracted from Granta Edupack)
- Poison's Ratio: 0.3
- Force: 1470 N.

The force was calculated considering the mass of the car door. The actual weight of the car door was considered as 25 Kg but considering the safety factor, the actual weight of the door was multiplied by 4 times and the extra 50 Kg weight was taken into account with the assumption some kids try to hang on the door. Therefore, overall weight of the door was taken as 150 Kg which was multiplied by gravitational force i.e., 9.81 to get the force acting on the rotational point of the hinge and the obtained force was **1470 N.**

The steps that were followed to carryout FEA analysis of Hinge are:

- **Mesh:** Tetramesh> 2D (trias) > 3D (tetras), Element order (first).
- **Loads:** (SPC)>(Forces).
- **Load Step:** (Linear analysis) > (SPC)>(Froces)
- **Material:** Young;s Modulus> Poison Ratio.
- **Properties:** (Assing Material) > Run Analysis .

Tetramesh was selected to create a shell mesh and fill the enclosed volume with solid elements and the **RBE2 elements** were created in between the nodes to specify the rigid connections. The mesh and the force applied has been shown in the **fig 43.**

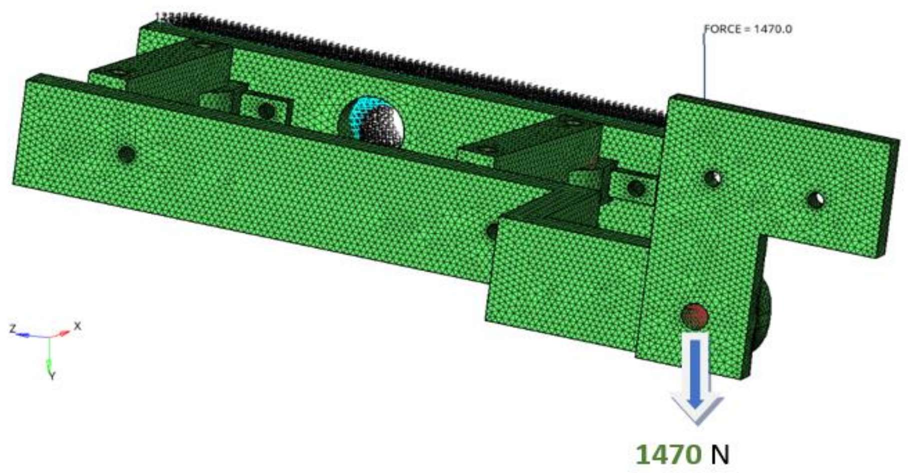


Figure 42: *Display the mesh and load applied in the hinge.*

Since the accuracy of the solution depends on various factors such as the element size, mesh density, the mesh convergence study was performed with different element size and the converged model **(i.e., 15mm mesh size)** was proceed forward for the stress and displacement analysis. The mesh convergence table and graph presented below indicates thet the solution has reached convergence. The plots exhibiting a steady-state behaviour, demonstrating that the solution values are no longer moving appreciably.

Table 7: *Mesh convergence analysis of stress and displacement with mesh size of 5, 7,15 (mm).*

S.N	Nominal mesh size (mm)	Max VM Stress (MPa)*	Max Displacement magnitude (mm)*
Model 1.hm	5	5.56E+01	3.12E-01
Model 2.hm	7	5.05E+01	2.97E-01
Model 3.hm	15	4.75E+01	2.54E-01

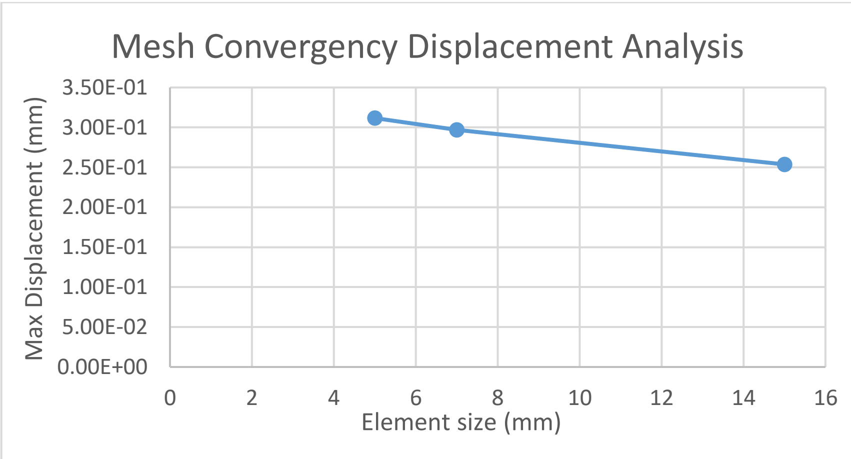


Figure 43: *Plot mesh convergence displacement against element size, 5,7and 15 (mm).*

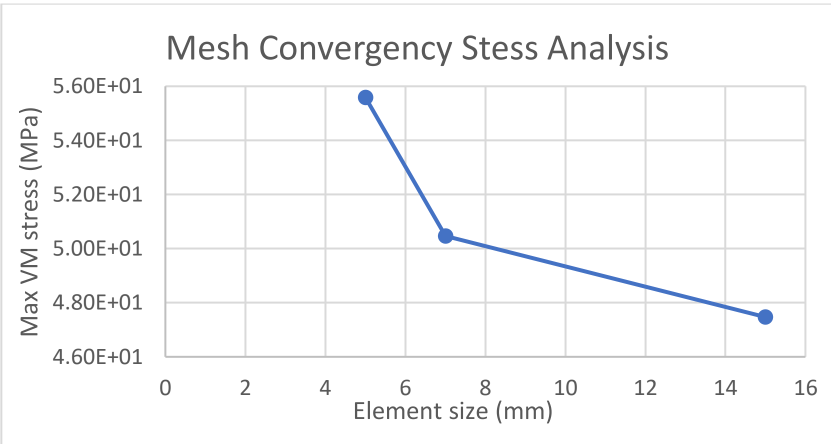


Figure 44: *Plot mesh convergence stress against element size, 5,7and 15 (mm).*

18.2. Results of FEA analysis

Initially, the displacement and the stress of the hinge were analysed.

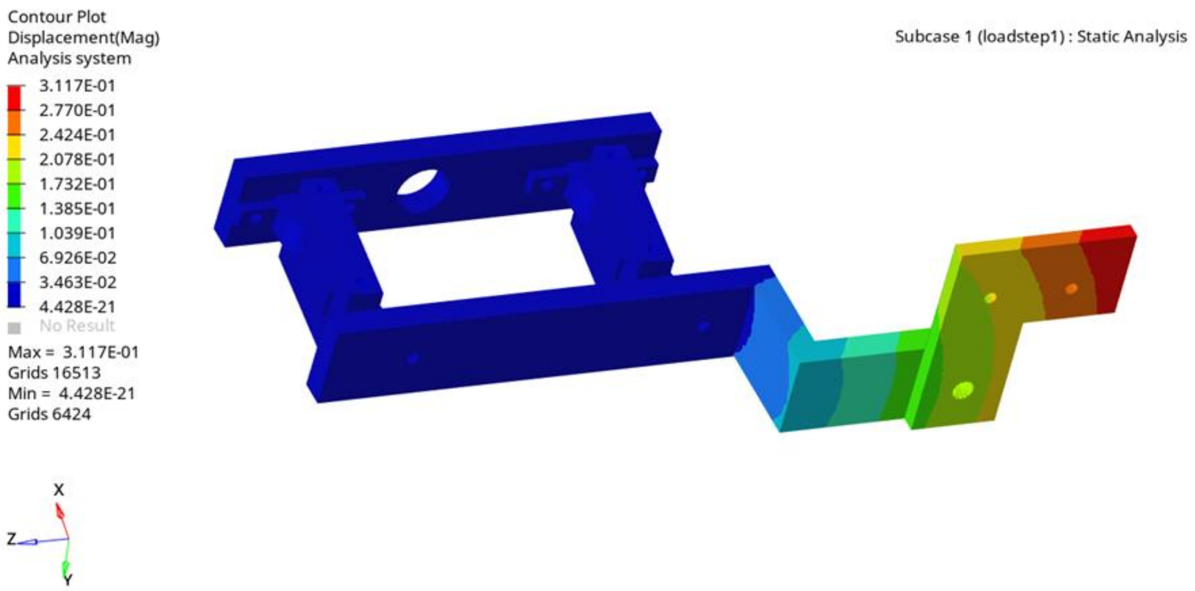


Figure 45:*Displacement analysis in Hyper Works. (units mm).*

The maximum displacement of the hinge was found to be **0.31mm** and it was at the tip of the rotational arm of the hinge. Farther the distance of the front arm of the door weight, the reduced impact or displacement can be observed.

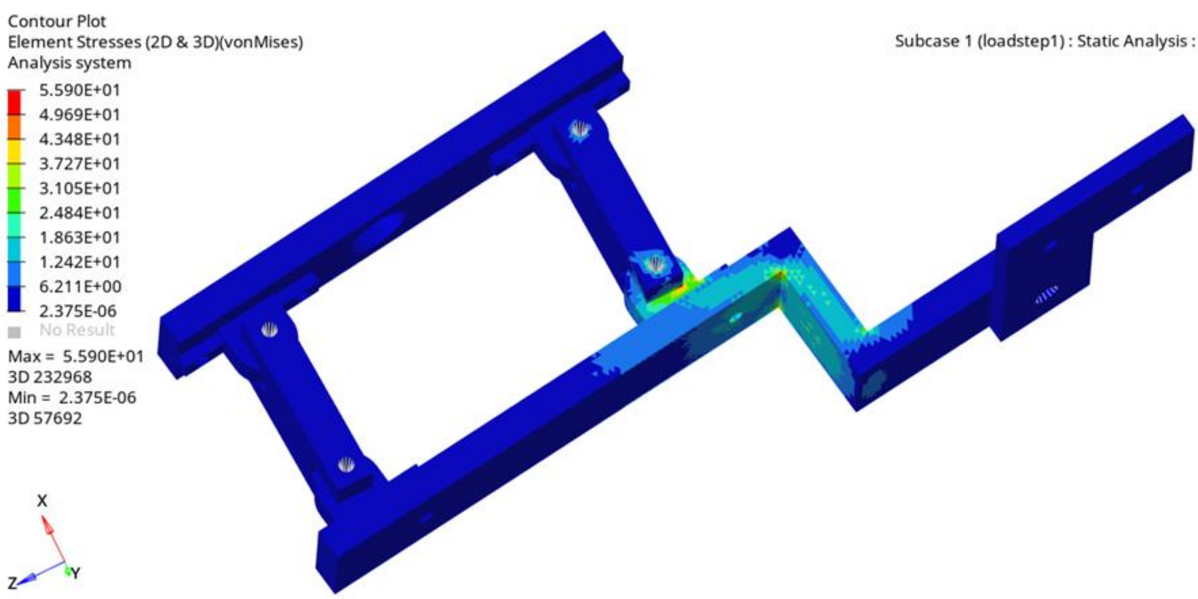


Figure 46:*Stress analysis in Hyper works. (units MPa).*

The maximum stress found to be **55.9 MPa** that is at the corner of bent portion of the front arm and at the connection of the front arm of hinge and the first linkage. The front arm of the hinge and the first connection point are the most stressed parts than any other hinge parts as shown in **fig 46.**

18.2.1.Factor of safety (FoS)

Yield Stress of low carbon steel (Y)= **255 MPA** **(Granta Edupack)**

Maximum stress found (Y_{max}) = **55.9 MPa**

$$\boldsymbol{FoS = \frac{Y}{Y_{max}} = 4.56}$$

18.3. Modal Validation

18.3.1.Reaction Forces (FEA)

To validate the FEA results, initially the forces at the nodes were observed and the hand calculation was performed to find the reaction at the these nodes. The reaction forces of the model were determined using a single point of constraint force (SPCF).

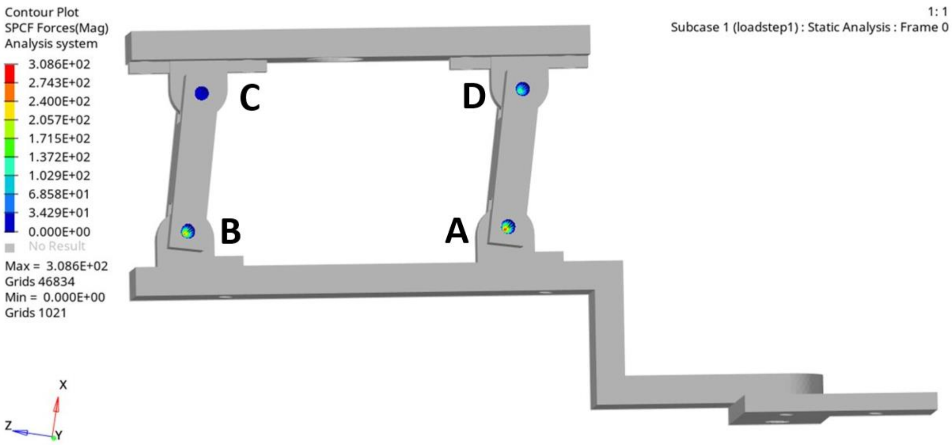


Figure 47: *Reaction forces at the nodes found using Hyper works.*

Table 8: *Results of the reaction forces obtained using Hyper works.*

Node ID	Contour (SPCF Forces) [N]
A	308.6
B	272.52
C	341.6
D	158.1

18.3.2.Validation with hand calculation

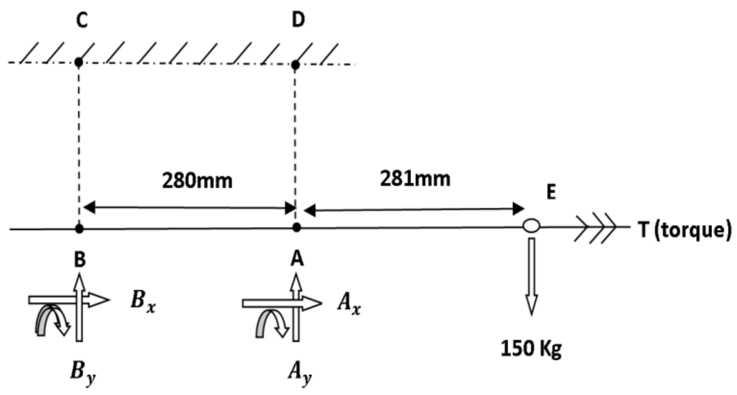


Figure 48: *Free body diagram of the hinge.*

Assumptions:

- Front arm of the hinge assumed to be Straight.
- Linkages are assumed to be held straight at half-open condition although there is certain angle between arm and the linkage. Since, the forces at front and rear pin connection experiences equal and opposite forces.

Calculation:

$\sum F_y = 0$ **(sum of all the forces is equal to zero)**

- $A_y + B_y - 150 = 0$ **equation: 1**

$\sum M_{B_y} = 0$ **(sum of all the Moments is equal to zero)**

- $A_y * 280 - 150 * (281 + 280) = 0$ **equation: 2**

$A_y = 300.54\ N\ (Force\ re4acting\ in\ upward\ direction)$

$B_y = -150.54\ N\ (Force\ reacting\ in\ downward\ direction)$

$A_y = -D_y\ (The\ force\ in\ A\ and\ D\ should\ be\ equal\ and\ opposite\ to\ balance\ the\ hinge)$

$-B_y = C_y\ (The\ force\ in\ B\ and\ C\ should\ be\ equal\ and\ opposite\ to\ balance\ the\ hinge)$

Table 9: *reaction forces obtained from Hand Calculation*

A_y	B_y	C_y	D_y
300.54 N (upward)	**150.54 N** (downward)	**150.54 N** (upward)	**300.54 N** (downward)

The force at nodes A calculated numerically and mathematically are very close with only difference of 8 N whereas the average of 125 N foce difference can be seen on the remaining 3 nodes i.e., B, C, and D which was expected as certain assumptions were made before the hand calculation. Similarly, it can be ensured that the hinge is balanced and calculation is correct as the forces exerted at the front and rear connections of the hinge are equal in magnitude and opposite in direction during straight linkange condition.

Percentage error:

- Overall reaction force found mathematically: **902.17**
- Overall reaction force found numerically: **776.8 N**

$$\Rightarrow \frac{\mathbf{902.17-776.8}}{\mathbf{902.17}} * \mathbf{100\%} = \mathbf{13.9\%}$$

Since, the percentage difference between the forces calculated between numerical method and the mathematical method is **13.9%** which is not significant and can be validated as the certain assumptions has been made during hand calculation which lead to increase in percentage error between two models.

18.4. Modal Shape Analysis

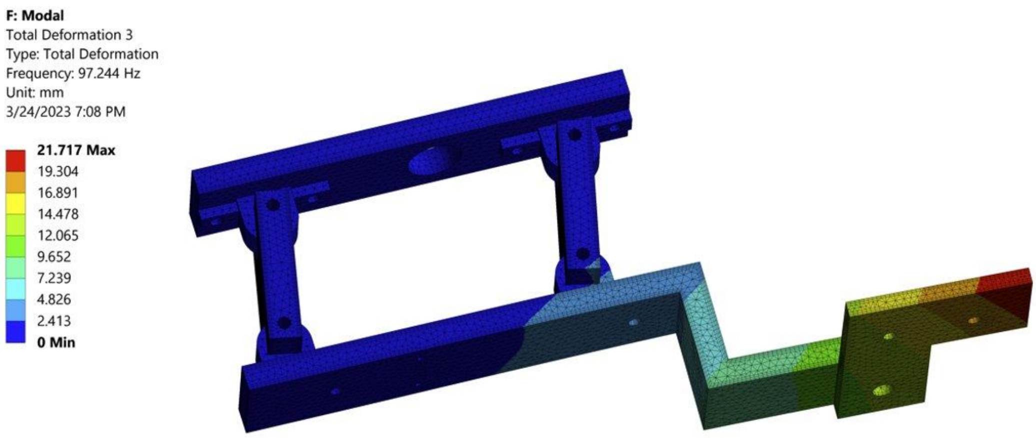


Figure 49: *Modal Shape of hinge at frequency 97.244 Hz.* ***[Ansys]***

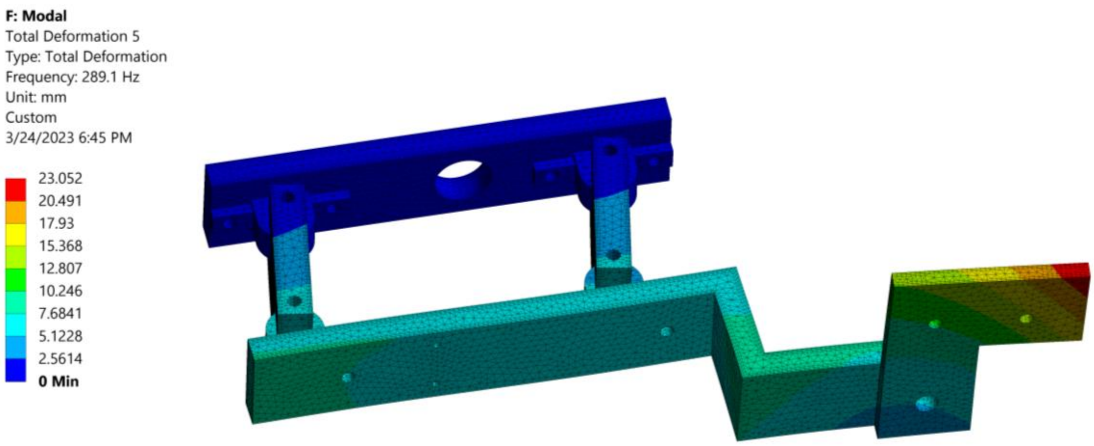


Figure 50: *Modal Shape of hinge at frequency 289.1 Hz.* ***[Ansys]***

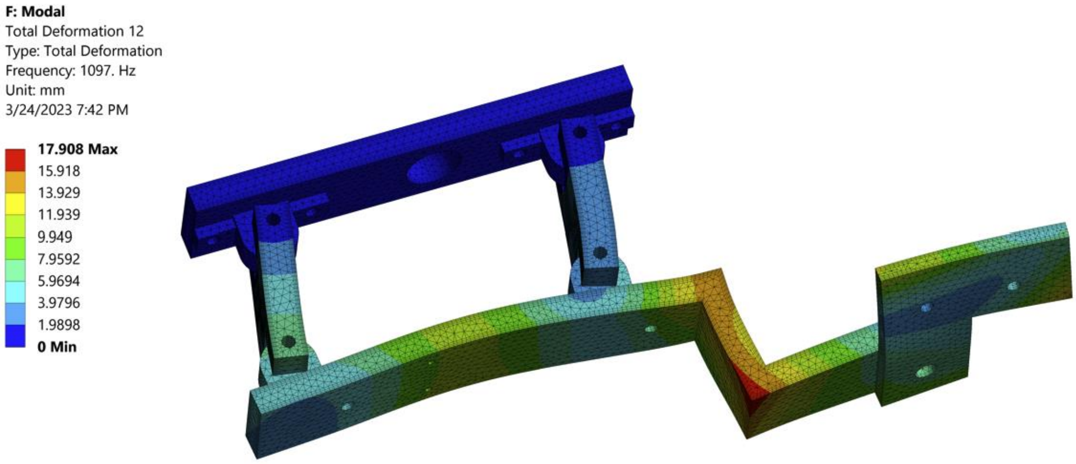


Figure 51: *Modal Shape of the hinge at frequency 1097 Hz.* ***[Ansys]***

The mode shape analysis was performed in Ansys to determine the shape of the Hinge at different frequencies. It was found that the deformation **starts** at the frequency of **97.244 Hz** with a maximum deflection of **21.71 mm.** Similarly, at the frequency of **289.1 Hz**, all parts of the front arm and most of the linkage parts experiencing the approximate displacement of **7.6 mm** and the maximum displacement was **23.052 mm** which is at the tip of the rotating arm. At the frequency of **1097 Hz,** although the maximum displacement is quite low as ccompared i.e., **17.908 mm**, the middle section of the front arm has got the higher displacement of **11.939 mm.**

18.5. Optimization of Hinge Designs

The front arm of the hinge and the connecting point were the highly stressed part of the hinge found. The optimization of the front arm of the hinge has been done to minimize the stress and deformation at that part. Similarly, the other objective to carry out the optimization was to reduce the weight and the volume of the hinge.

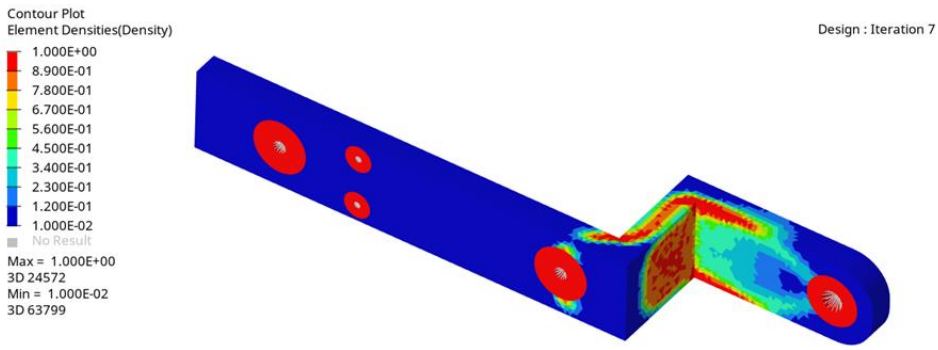


Figure 52*: Counter plot showing density change during optimization.* ***[Hyper Works]***

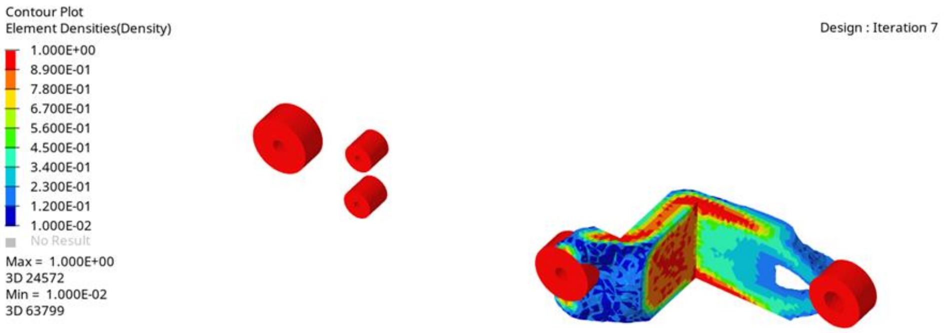


Figure 53: *Iso View of counter plot showing density change during optimization.*

18.5.1.Optimization Result.

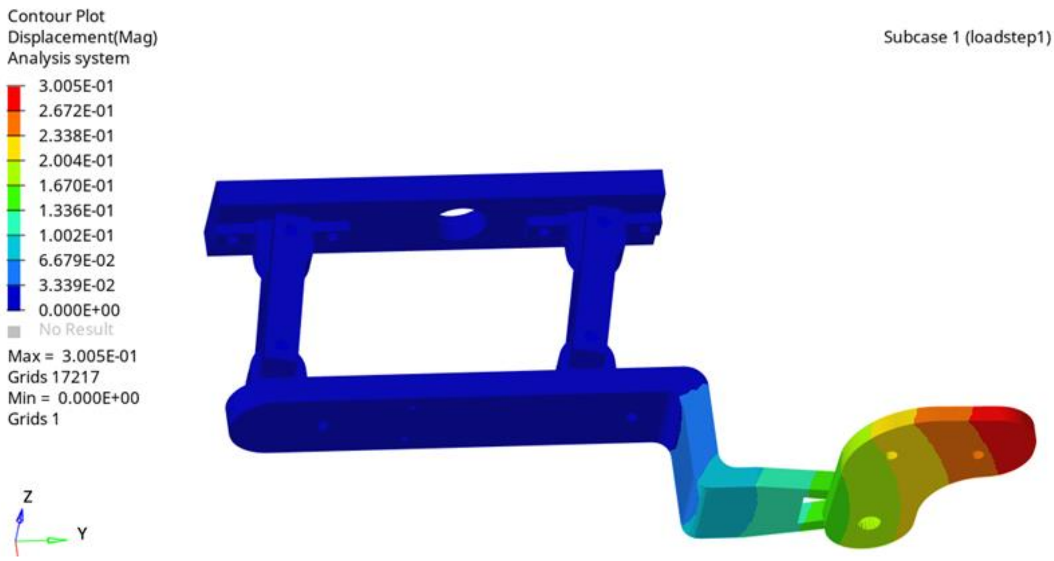


Figure 54*: Displacement analysis after design validation.* ***[Hyper Works]***

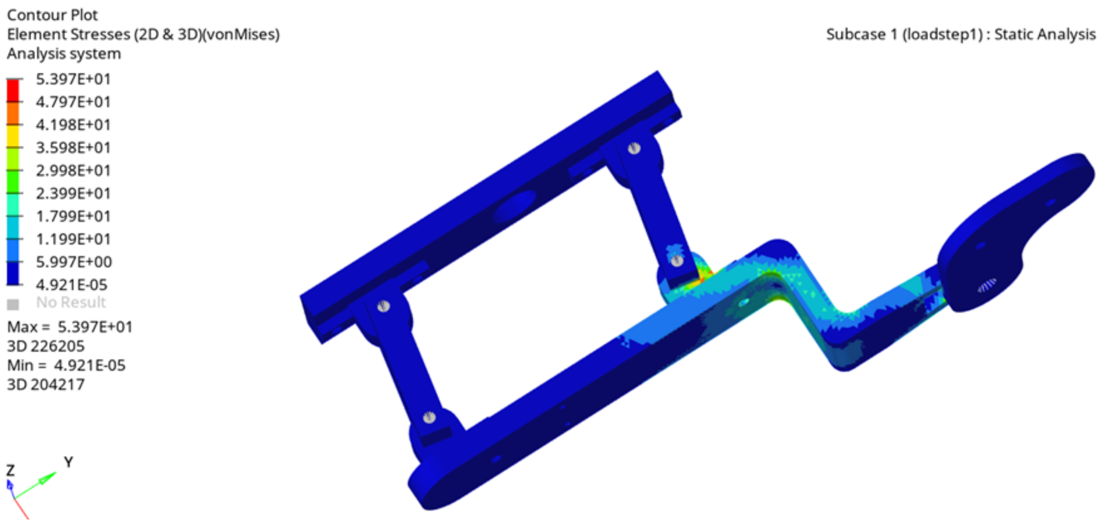


Figure 55: *Stress analysis after design validation.* ***[Hyper Works]***

Results after Optimization:

- Maximum displacement = **0.30 mm**
- Maximum stress = **53.9 MPa**
- Mass of front arm = **1193.716 g**
- $\boldsymbol{FoS = \frac{Y}{Y_{max}} = 4.73}$

Results before Optimization:

- Maximum displacement = **0.31 mm**
- Maximum stress = **55.9 MPa**
- Mass of front arm: **1371.933 g**

The opimization resulted in the reduction of stress by **2 MPa** and the displacement by **0.1 mm** which is quite low. The stress could have been further minimized considering all the highly stressed part of the hinge as only the front arm of the hinge has been optimized. Optimization of rotating arm would essentially decrease the displacement as it was the highly displaced part but it wasn't considered for the optimization. The mass of the hinge has been successfully reduced by **178.2 g** and if all the parts of the hinge were considered for the optimization then the weight of the hinge could be decereased significantly. The factor of safety has been increased by **0.17** as the highly stressed part of the front arm of the hinge was minimized.

18.6. Concluding FEA Analysis and Design Optimization

The factor of safety achieved can be considered higher and taking advantage of higher factor of safety, the hinge could be made lighter. The maximum displsacement on the hinge i.e., **0.3 mm**, indicates that the hinge can withstand the expected loading conditions without experiencing significant deformation or failure. The optimization of the full hinge would give better optimized results than only optimizing the front arm of the hinge.

19. DFMEA

***Table 10:** Design Failure Mode and Effect Analysis of hinge mechanism.*

DFMEA Template																			MEADinfo Product
Prepared By:											FMEA No/Rev: 0000/01								
Date: 00/00/00											Process/Component: Glovebox								
														Action Results					
Item	Function	Potential Failure Mode	Potential Effects of Failure	Severity	Potential Causes of Failure	Occurance	Current Controls for Prevention	Detection	Detection	RPN	Recommended Action	Responsibility and Target Completion Date	Action Taken	Svrty	Ocrnc	Dtctn	RPN		
Hinge	connect two components keeping them alligned while supporting the weight of the door	Hinge becomes dislocated and misalignment	Door will not operate fully	5	Improper installation	4	Ensure componets geometrically alligned and minimise hole clearance	Vibration analysis, laser shaft analysis to detect coupling offsets	2	40	Visual revision of the correct aligned of the door to the frame	20/03/2023	sufficiend space considered for screw thread and selection of appropriate screws considering tolerances.	5	2	2	20		
		Hinge Fracture	Door could come off and injure surrounding people	9	Bad material selection and excessive loading	3	Ensure Suitable material is selected by comparing properties such as Young's Modulas and Ultimate tensile strength of materials.	calculating forces resulting from the weight of the door, wind resistance.	2	54	Complete tensile, compressive and fatigue tests to determine stregth values for materials. Use of extra suppot.	20/03/2023	calculation of forces acting on the hinge. Double linkage introduced instead of one.	9	2	2	36		
			Door may come off and cause damge to other components such as the latch and striker	9	Wear and tear overtime due to regular use	3	Stainless steel has been selected due to its high resistance to wear and tear.	routinely visual inspection	2	54	Selection of proper material and use of protective coating.	20/03/2023	Stainless steel has been selected due to its high resistance to wear and tear.	9	2	2	36		
		Poor lubrication	Door may have slow and rough operation	4	Lack of maintenance	7	Use of Silicone-based lubricant or grease to keep the hinges moving smoothly	Abnormal noise and vibration duing door in use	1	28	Systematic lubrication	20/03/2023	Use of Silicone-based lubricant or grease to keep the hinges moving smoothly	4	5	1	20		
Linear Actuator	Push/pull the door	fails to keep/push door in primary position and failure to keep/pull into secondary position	Door will not operate fully	7	insufficient power provided by motor and faulty wiring, control communication error	2	Ensure motor in the linear actuator has sufficient capacity to lift door, use of high quality electrical components	buzzing noise from component, inspect wiring	2	28	Choosing appropriate shock and vibration testing standards of linear actuator such as IEC.	20/03/2023	Linear actuator with 8-35V 1500N Motor selected after calculation of force required to operate door	7	1	2	14		
	act as secondary support of the door	Door weight no longer fully supported	Door may become loose	6	Excessive loading and side loading	2	Ensure the linear actuator of suitable material is selected by comparing properties such as Young's Modulas and Ultimate tensile strength of materials	Door will have slow and eratic operation	2	24	Complete tensile, compressive and fatigue tests to determine stregth values for materials	20/03/2023	Zinc-Aluminium alloy selected as a material due to its high yield strength.	6	1	2	12		

Latch and latch retainer	*Allow door to be opened and hold door closed*	*door cannot be locked*	*Items from the car can be stolen and car will not be secured*	*6*	*Excessive slamming*	*4*	*Ensure Latch and latch retainer are compatible. Pull or push test to evaluate the latch's ability to withstand impacts and other forces.*	*Visual Inspection, Endurance testing to identify possible latch failure*	*1*	*24*	*Use of latch position sensors to detect any potential abnormalities in latch mechanism position*	*20/03/2023*	*MLX92212 hall effect latching sensor. Implementation of manual lock.*	*6*	*2*	*1*	*12*
Screw/Bolt	*Connect components*	*Screw become loose*	*Components may become dislocated*	*5*	*angle offset, misalignment*	*5*	*Ensure componets geometrically alligned and minimise hole clearance*	*Direct observation, compression indicator, vibration detector*	*6*	*150*	*Visual revision of the correct aligned of the door to the frame. Spring washers could be used.*	*20/03/2023*	*sufficiend space considered for screw thread and selection of appropriate screws considering tolerances.*	*5*	*3*	*6*	*90*
		Screw Fracture	*Door will not operate fully*	*6*	*Over-tightening*	*4*	*Ensure Component dimensions and strength are sufficient for mechanism*	*Inspect screws for material and hydrogen embrittlement and stress corrosion cracking*	*3*	*72*	*Replace damged screws with the consideration of its strength.*	*20/03/2023*	*Use of multiple screws. Stresses at the screws are calculated. Stainless steel selected as a material due to its high yield strength.*	*6*	*2*	*3*	*36*
		Poor lubrication	*Door may have slow and rough operation*	*4*	*Lack of maintenance*	*7*	*Use of Silicone-based lubricant or grease to keep the hinges moving smoothly*	*Abnormal noise and vibration duing door in use*	*1*	*28*	*Systematic lubrication*	*20/03/2023*	*Use of Silicone-based lubricant or grease.*	*4*	*4*	*1*	*16*
			Abnormal sound							*0*							*0*
Nut	*fastener that provides a clamping force and prevents axial load*	*Nut thread failure*	*Deformation or dislocation of bolt*	*6*	*Bolt thread stressed or misaligned*	*5*	*Ensure componets geometrically alligned and minimise hole clearance*	*Direct Observation, compression indicator, vibration detector*	*6*	*180*	*Investigate and replace damaged nuts and lubricate timely*	*20/03/2023*	*N/a*	*6*	*5*	*6*	*180*
Bearing	*Allow anti-clockwise movement of door about the pivot*	*bearing stuck allowing no rotation in any plane*	*Breakage in hinge front arm, door loses stability and becomes unsafe*	*7*	*Excessive loading , Improper mounting, false brinelling*	*3*	*Ensure componets geometrically alligned and minimise hole clearance*	*Vibration detector, to analyse the ability of the bearing to function efficiently*	*3*	*63*	*Investigate and replace damaged bearing and lubricate timely*	*20/03/2023*	*6mm I.D,17mm O.D RS PRO Deep Groove Bearing, static load rating 604.8kN, dynamic load rating 1627.2kN*	*7*	*2*	*3*	*42*
		Bearing Fracture	*Dislocate linear actuator from car body*	*7*	*Fatigue spalling, wear, abrasive contamination, excessive preloading*	*2*	*Ensure Component dimensions and material strength are sufficient for mechanism*	*Excessive noise and vibration*	*3*	*42*	*Replace bearing if found faulty*	*20/03/2023*		*7*	*2*	*3*	*42*
		Poor lubrication	*Door may have slow and rough operation*	*4*	*Lack of Maintenance*	*7*	*Use of Silicone-based lubricant or grease to keep the hinges moving smoothly*	*Abnormal noise and vibration duing door in use*	*2*	*56*	*Systematic lubrication*	*20/03/2023*		*4*	*3*	*2*	*0*

Sealing	*Waterproofing, Noise reduction, pressure control, climate control inside of the car*	*Tear in car seal*	*reduced fuel efficiency due to increased aerodynamic drag*	*6*	*Incorrect installation and not the correct use of adhesive*	*5*	*Ensure proper seal selection by considering system operating pressure, seal material compatibility with fluid and fluid operating temperature, resistance against extrusion, expected service life*	*Direct observation of the sealing in the frame of the car door. loud popping sound*	*2*	*60*	*Proper material selection for the sealing. Incase of tear replace sealing.*	*20/03/2023*	*Black closed cell neoprene/epdm foam strips used*	*6*	*3*	*2*	*36*
			leakage of water and air inside car, increased noise.	*6*	*Wear and tear overtime due to regular use*	*5*	*Tensile strength tests for different materials,*	*Partial or total sealing off of the frame*	*2*	*60*	*Use protective coating to help prevent damage from UV rays, moisture, and other environmental factors.*	*20/03/2023*	*Use of silicone coating*	*6*	*3*	*2*	*36*
		AB flange improper engagement	*Fluid leakage*	*6*	*Uneven distrubution of compression force, stress relaxation, missalignment*	*4*	*Ensure design is compatible with flange dimensions and select appropiate gasket*	*ultrasonic test to detect air leaks using high frequency sound waves, Visual inspection*	*3*	*72*	*Perform sound test to check for wind noise, if neccesary replace flange and/or gasket*	*20/03/2023*	*Use a dial indicator to ensure shaft allignment*	*6*	*3*	*3*	*54*
linkage	*Convert motion and direction of door by altering angle between car body and door*	*Linkage Fracture*	*Door will not operate*	*8*	*Excessive loading*	*2*	*Ensure Suitable material is selected by comparing properties such as Young's Modulas and Ultimate tensile strength of materials*	*Calculate forces resulting from the weight of the door*	*2*	*32*	*Complete tensile, compressive and fatigue tests to determine stregth values for materials*	*20/03/2023*		*8*	*1*	*2*	*16*

Failure mode effect analysis (FMEA) is a structured approach to identifying possible failures of every component in the system and the risks associated and take steps to mitigate and eliminate those risks. It aims to decrease the severity and occurrence of failure modes while increasing the ability to detect them. FMEA displays the effects, causes, current controls for prevention and detection method for each possible failure mode. Each failure mode must be rated from 1-9 for severity of effect, likelihood of occurrence, and ability to detect in accordance with AIAG compelled rating. The product of these values are calculated to give the risk priority number (RPN). For each failure mode an action must be recommended and the effect on the RPN value should be recorded.

The FMEA completed for the car door system is shown in **table 10**. The Hinge has 3 possible failure modes, the most significant failure mode was hinge fracture as this would result in the most severe consequences. Hinge fracture had an original RPN value of 54 however this reduced to 36 after the recommended actions were taken. Calculating the forces acting on the hinge is helpful for accurately selecting a material that can sufficiently supress the stresses experienced by the hinge, this will decrease the likelihood of hinge fracture occurring. With the use of a double linkage mechanism, if one linkage fails the other will be sufficient for the hinge to function reducing the severity of this failure. The linear actuator has 2 possible failure modes of which failure to operate door is the most severe. This failure mode had an original RPN value of 28 which then reduced to 14 after recommended actions were taken. Calculating the force required to open/close the door and move it into the desired position allows a sufficient motor to be selected. In addition to selecting an appropriate motor the use of high-quality electrical components when configuring wiring will reduce the occurrence rating as the chance of failure is reduced. The latch and latch retainer locking system had one failure mode which was the inability to lock the door. This had an original RPN value of 24 which was reduced to 12 after recommended actions were taken. The use of a high quality sensors allows better detection of latch misalignment. The screws and bolts had 3 failure modes, of which screw/bolt fracture was the most severe due to the difficulty to detect failure of a single screw the RPN value is very high. This failure mode had an original RPN value of 150 which was reduced to 90 after recommended actions were taken. By calculating the stresses experienced by the screws and bolts, appropriate screw/bolt material and dimensions can be selected, this will reduce the occurrence of failure. The bearing had an original RPN value 63 which was reduced to 42 after selecting a deep groove ball bearing with a high static and dynamic load rating decreasing the occurrence of failure. The sealing of the car door had two potential failure modes, tear in car seal and AB flange improper engagement. The failure mode tear in car seal had an original RPN value of 60 which was reduced to 36 after recommended actions were taken. This was because the use of the EPDM/neoprene composite rubber strips will reduce the occurrence of this failure due to it being selected while considering the sealing operating conditions. The failure mode AB flange improper engagement had an original RPN value of 72 which was reduced to 54 after recommended actions are taken. The use of a dial indicator to ensure shaft alignment would reduce the occurrence of improper engagement as it reduces the chance of misalignment.

20. Ergonomics

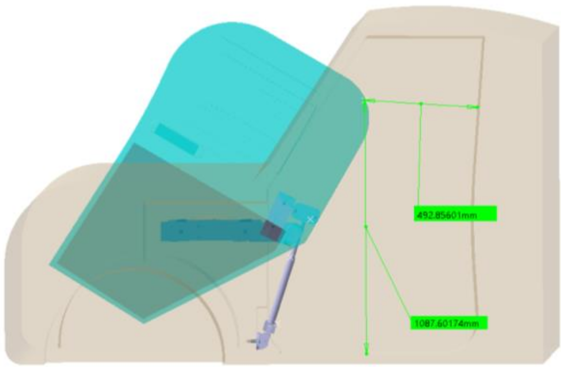


Figure 56: *Design showing the width* and height of the door opening

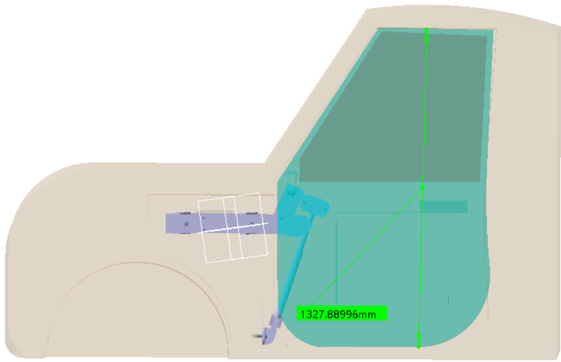


Figure 57: *Design showing height of the* door.

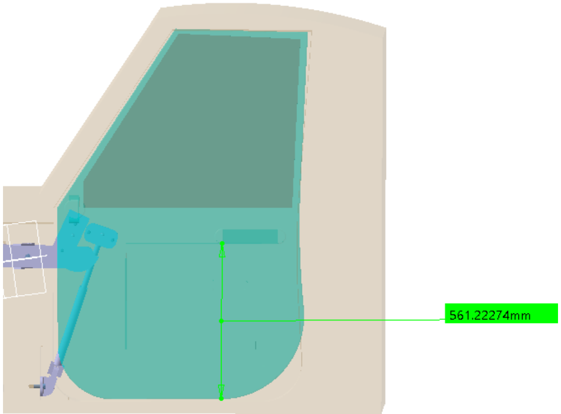


Figure 58: *Design showing the height from bottom of the door to handle.*

This design, when the door is open, provides a maximum opening 493.599mm in width and 1325.31mm in height as demonstrated in **fig 55.** A 95th percentile male has a hip breadth of 376.5mm and a sitting height of 971.9mm therefore this opening is sufficient for comfortable ingress/egress of the vehicle for a 95th percentile person.

Door handle should be located so that it is easy to reach and operate from both inside and outside the car. Lateral position of the outside door handle should be rear most position of door edge. Height of outside handle not above 5th percentile female standing shoulder height which is (124cm) and not below 95th percentile male hand height (63cm) calculated by adding anthropometric data for hand length(21cm) elbow-wrist length(31cm) and shoulder-elbow length (39) and taking the total away from the shoulder height(154cm) for a 95th percentile man. Inside door handle should be below sitting shoulder height of a 5th percentile female (50.9cm) and above sitting waist height of a 95th percentile male (31.58cm).

The door handle will be made easily visible. This will be done by using a contrasting colour to the car body or adding reflective material to the door handle. Designed to have a unique shape to standout. Use of LED lights on the inside of handles to appear more visible.

Another ergonomic requirement of the car door is to provide good sound isolation to minimise noise from outside the car. This can be done by a combination of sound deadening materials such as acoustic foam and butyl rubber and sound-absorbing materials such as open cell foam. Additionally, the use of acoustic glass instead of standard glass will greatly improve noise reduction.

The side pockets of the door will have a cover which will remain shut unless held open to prevent items from falling out of the pocket when the door is in use. They will also feature close control dampers to prevent the cover slamming on fingertips and to reduce the noise level when closing.

21. Conclusion

The report concludes that the steps and procedures taken into account to generate the new mechanism of the door opening and closing is successfully achieved. Almost all the client's requirements are met, which includes opening the door within a range of 2500 mm, minimizing vibration and noise, creating a high-quality appearance, improving the seal, and achieving an acceptable opening and closing speed of the door. The mechanism found out to be lot cheaper (£199.47) than the other car door hinge such as Lambo door hinge (£1096.67) (DemonTweeks, n.d.) where the manufacturing cost, assembly cost, volume of a material and cost of pre-available products in the market used in this mechanism are considered. The FEA analysis has been conducted to find out the stresses and displacement on the hinge due to the weight of the door and the factor of safety was found out to be 4.56 which is quite high, suggested that the hinge can be optimized and can be made lighter. This requires less material and contribute to the sustainability too. The sustainability emphasized in contributing environmental protection, economic profit, and social equity, which was achieved considering the availability of materials, its life cycle, transportation, manufacturing process and cost. The optimization was performed on the front arm of the hinge which successfully able to reduce the weight of the mechanism by 173 g and stress by 2MPa without losing the factor of safety while the optimization of overall mechanism should have been performed to achieve better result. The DFMEA shows that the severity of the design couldn't be able be minimized but the occurrence of the failure mode has been successfully minimized after the action taken to prevent the possible failures. The ergonomics considered shows the maximum opening of the door (493.599mm) in width and (1325.31mm) in height, which provides sufficient space for ingress and egress of the vehicle for a 95th percentile person. Other ergonomics include the position of the door handle, design of a car door pocket, sound isolation.

22. References

Amazon. (n.d.). *ECO-WORTHY 2pcs 8 Inch Heavy Duty Linear Actuator*. Retrieved from Amazon.co.uk: https://www.amazon.co.uk/ECO-WORTHY-Actuator-Wireless-Controller-Brackets/dp/B01LW04214/ref=asc_df_B01LW04214/?tag=googshopuk-21&linkCode=df0&hvadid=501102159241&hvpos=&hvnetw=g&hvrand=14906044001546247083&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint

Amazon. (n.d.). *Front Door Frame Sealing*. Retrieved from https://www.amazon.co.uk/256inch-Weather-Excluder-Proofing-Replacement/dp/B0BJZC4MW2/ref=sr_1_9?keywords=PVC+Door+Seal&qid=1676911663&sr=8-9

Amazon. (n.d.). *Pivot Hinge*. Retrieved from Amazon: https://www.amazon.co.uk/Stainless-Rotation-Suitable-Household-Cabinets/dp/B094JCJJXV?source=ps-sl-shoppingads-lpcontext&ref_=fplfs&psc=1&smid=A2T0SXP96J5YNT

Amazon. (n.d.). *Qishare Silicone Rubber Weather Strip*. Retrieved from https://www.amazon.co.uk/Qishare-Multi-Hole-Professional-Soundproof-D9x6MMx6Mx1/dp/B08GXCTBH4?th=1

Autodeal. (n.d.). *Car door handles: Why there are so many different types*. Retrieved from https://www.autodeal.com.ph/articles/car-features/car-door-handles-why-there-are-so-many-different-types

Autodeal. (n.d.). *Car Door Rubber: Maintenance and Replacement*. Retrieved from https://www.autodeal.com.ph/articles/car-features/car-door-rubber-maintenance-and-replacement

Autodoc, 1. (n.d.). *BLIC 6802-00-9524452P Hinge, bonnet* . Retrieved from AutoDoc: https://www.autodoc.co.uk/blic/7610502?gshp=1&gclid=Cj0KCQjwtsCgBhDEARIsAE7RYh2oZS_VxtVDQZVxgaJH8T92Y-DLq2FeqZ_WIxtTw8P0uLe0gYZqImwaAh4AEALw_wcB

Autoevolution. (n.d.). *The Main Types of Li-Ion Batteries Explained and What Is the Best for Electric Vehicles*. Retrieved from https://www.autoevolution.com/news/the-main-types-of-li-ion-batteries-explained-and-what-is-the-best-for-electric-vehicles-181498.html

AUTOFREAK. (2015, 10 05). *ALL ABOUT AUTOMOBILES*. Retrieved from Heabrnmadewithengines.: https://heavenmadewithengines.wordpress.com/tag/swan-doors/

Autojosh. (2019, 09 17). *10 Types Of Car Doors You Need To Know* . Retrieved from Autojosh.: https://autojosh.com/10-car-door-types-you-need-to-know-photos/

Axom, G. (nd, nd nd). *The ten best cars with suicide doors*. Retrieved from Goodwood.com: https://www.goodwood.com/grr/road/news/2022/10/the-ten-best-cars-with-suicide-doors/

Bearings, S. (n.d.). *Budget LFR50/5-62RS Yoke Type Track Roller with U Groove 5x17x7/8mm*. Retrieved from Simply Bearings: https://simplybearings.co.uk/shop/product_info.php?products_id=42819&vat_inc=true&gclid=Cj0KCQjwtsCgBhDEARIsAE7RYh37WCZ2ZxkBEI0CJSX_dsWvtaVWe5RsbnHQ5HcA-X5uxAREyn5LnEEaAk3ZEALw_wcB

CO., T. s. (n.d.). *JOHN DEERE 150A ALTERNATOR AL119537 AL171541*. Retrieved from https://www.startermotoralternators.co.uk/products/john-deere-150a-alternator-al119537-

al171541?variant=42880068911312&currency=GBP&utm_medium=product_sync&utm_source=google&utm_content=sag_organic&utm_campaign=sag_organic&gclid=EAIaIQobChMIxeWf8r6k_QIVkL

Components, E. (n.d.). *types of hinges and where to use them*. Retrieved from Essentra Components: https://www.essentracomponents.com/en-gb/news/solutions/access-hardware/types-of-hinges-and-where-to-use-them

Components. (n.d.). *RS PRO Black EPDM Edge Protection, 20m.* Retrieved from https://uk.rs-online.com/web/p/door-seals/6191635?cm_mmc=UK-PLA-DS3A-_-google-_-CSS_UK_EN_Security_%26_Ironmongery_Whoop-_-Door+Seals_Whoop+(2)-_-6191635&matchtype=&pla-340963375806&cq_src=google_ads&cq_cmp=10914490521&cq_term=&cq_plac=&cq_net=g&cq_plt=gp

Components., R. (n.d.). *RS PRO Hybrid Stepper Motor, 12 V, Unipolar, 1.8°, 6.35mm Shaft*. Retrieved from https://uk.rs-online.com/web/p/stepper-motors/1805283?cm_mmc=UK-PLA-DS3A-_-google-_-CSS_UK_EN_Automation_%26_Control_Gear_Whoop-_-Stepper+Motors_Whoop-_-1805283&matchtype=&aud-1340734711647:pla-349346082923&cq_src=google_ads&cq_cmp=9771206608&cq_term=&cq_

Control., M. (n.d.). *Spur gears: What are they and where are they used?* Retrieved from https://www.motioncontroltips.com/spur-gears-what-are-they-and-where-are-they-used/

Davies., G. (2012). *Materials for Automotive Bodies.* (Firts Edition. ed.). Kidlington, Oxford,England.: Elsevier Ltd.

DemonTweeks. (n.d.). *DemonTweeks*. Retrieved from LSD Lambo Look Door Kit: https://www.demon-tweeks.com/uk/lsd-lambo-look-door-kit-kwa50080014/

DGS. (n.d.). *Composite Door Hinges (Flat)*. Retrieved from Composite Hinge: https://dgsgroup.co.uk/door/hinges/composite-hinge/

Ebay. (nd, nd nd). *Brand New Four Suicide Door Heavy Duty Hidden Hinges Rat Rod 2 Door Kit Weld In*. Retrieved from Ebay: https://www.ebay.com.au/itm/273726304673

Ebay. (nd, nd nd). *Vertical Door Hinges Bolt Kit Butterfly 90° Car Doors Universal Lambo Scissor*. Retrieved from Ebay: https://www.ebay.com/itm/255474271068

Eclipse. (n.d.). *Grade 13 Ball Bearing Fire Door Hinge Satin Finish*. Retrieved from Tool Station: https://www.toolstation.com/grade-13-ball-bearing-fire-door-hinge/p73733

Edel. (n.d.). *1019136A01 TOP ROLLER DOOR WITTUR-SELCOM DELRIN*. Retrieved from Edel: https://edelcomponents.com/gb/carriage-operator-pulleys/2396-1019136a01-top-roller--door-wittur-selcom-delrin

Fregot. (n.d.). *Restoration and coating of shafts, rollers and wheels with rubber or polyurethane.* Retrieved from Fregot: https://www.fregat.co.uk/pokritie_poliuretanom

Gears, K. (n.d.). *HELICAL GEARS*. Retrieved from https://khkgears.net/new/helical_gears.html

Halfords. (n.d.). *Halfords 096AGM Start/Stop AGM 12V Car Battery 5 Year Guarantee*. Retrieved from https://www.halfords.com/motoring/batteries/car-batteries/halfords--096agm-start%2Fstop-agm-12v-car-battery-5-year-guarantee-548638.html?istCompanyId=b8708c57-

7a02-4cf6-b2c0-dc36b54a327e&istFeedId=367c5610-f937-4c81-8609-f84582324cd6&istItemId=wiixaiqx&is

howacardoorsworks.com. (nd, nd nd). *Renewing door hinge pins and hinges*. Retrieved from howacardoorworks: https://www.howacarworks.com/bodywork/renewing-hinge-pins-and-hinges

Hydraulics, V. (n.d.). *Through Rod Cylinder*. Retrieved from https://valleyhydraulics.co.uk/portfolio/through-rod-hydraulic-cylinder/

Johnnylawmotors. (nd, nd nd). *AutoLoc 2 Door Universal Heavy Duty Gullwing Door Hinge Set Kit - Includes Hinges, Hardware, Hardened Steel Mounting Blocks, Reinforced Brackets, & Heavyweight Hinge Pins for Custom Car Truck Hot Rod*. Retrieved from Johnnylawmotors. : https://www.johnnylawmotors.com/catalog/frame-body-parts/door-hinges/gullwing-door-kits/10015477/gullwing-hinges?attribute-102=1468

Kelston. (n.d.). *How does the worm and wheel work?* Retrieved from https://www.kelstonactuation.com/knowledge-base/worm-and-wheel

Limited, R. (n.d.). *SMC Pneumatic Piston Rod Cylinder - 32mm Bore, 125mm Stroke, CP96 Series, Double Acting*. Retrieved from https://uk.rs-online.com/web/p/pneumatic-piston-rod-cylinders/9166720?cm_mmc=UK-PLA-DS3A-_-google-_-CSS_UK_EN_Pneumatics_%26_Hydraulics_Whoop-_-Pneumatic+Piston+Rod+Cylinders_Whoop-_-9166720&matchtype=&pla-475933774499&cq_src=google_ads&cq_cmp=12814832521

London., S. (n.d.). *Rollan 40 Sliding Door Fittings and Track 2800 mm*. Retrieved from https://www.sdslondon.co.uk/rollan-40-sliding-door-fittings-and-track-2800-mm.html?campaign=18082642293&content=&keyword=&gclid=EAIaIQobChMI4rzDiL6k_QIVA9DtCh0ncwN2EAsYBiABEgI_CPD_BwE

Metalines. (n.d.). Retrieved from Metalines: https://metalines.com/

MISUMI. (n.d.). *Rota Stainless Steel H Type Heavy-Duty Door Roller*. Retrieved from MISUMI: https://uk.misumi-ec.com/vona2/detail/221005400240/

NSK. (n.d.). *NSK 51108 THRUST BEARING*. Retrieved from NSK: https://uk.rubix.com/en/axial-grooved-ball-bearing-512/p-G1235005240?gclid=CjwKCAiA0cyfBhBREiwAAtStHGI1Sz-lJNwqnnbAY-js9-_bTpOaecSwUI7DlSXzLWhDb-j_0IzwpxoComYQAvD_BwE

PCI. (n.d.). *Track Rollers*. Retrieved from PCI: https://www.pcimfg.com/products/track-rollers/

Plastic, C. M. (n.d.). *10mm Clear Polycarbonate*. Retrieved from Cut My Plastic: https://www.cutmyplastic.co.uk/polycarbonate-sheet/10mm/?gclid=CjwKCAiA0cyfBhBREiwAAtStHPG53dJJTqrc3aBTwKt2hz_segx5nL1CyGNF4F00ROiCzUrrU7bo7hoCrwgQAvD_BwE

PLASTICS.CO.UK. (n.d.). *PVC Grey Plastic Sheet - 5mm Thick*. Retrieved from PLASTICS.CO.UK: https://plasticsco.co.uk/products/pvc-grey-sheet-5mm-thick?variant=40501954642059

POLYMAX. (n.d.). *Neoprene / EPDM Foam Strips*. Retrieved from POLYMAX: https://www.polymax.co.uk/rubber-sheet/sponge-epdm-neoprene-foam-strips-sab

Procarparts. (nd, nd nd). *FORD TRANSIT Sliding Door Roller & Hinge / Right Bottom & Middle & Top.* Retrieved from Procarparts.: https://www.procarparts.co.uk/products/ford-transit-sliding-door-roller-hinge-right-bottom-middle-top

Pumilia, A. (2020). *A door opening system: from case studies to the design of a hinge system for small series vehicles.* POLITECNICO DI TORINO.

RS. (n.d.). *Pinet Aluminium Spring Hinge, Screw Fixing 67mm x 55mm x 4.5mm*. Retrieved from RS: https://uk.rs-online.com/web/p/hinges/9174582?cm_mmc=UK-PLA-DS3A-_-google-_-CSS_UK_EN_Security_%26_Ironmongery_Whoop-_-Hinges_Whoop+(2)-_-9174582&matchtype=&pla-390921293881&cq_src=google_ads&cq_cmp=10914490521&cq_term=&cq_plac=&cq_net=g&cq_plt=gp&gclid=C

RS. (n.d.). *SKF 35mm Bore Plain Bearing*. Retrieved from RS: https://uk.rs-online.com/web/p/plain-bearings/2372272?cm_mmc=UK-PLA-DS3A-_-google-_-CSS_UK_EN_Bearings_%26_Seals_Whoop-_-Plain+Bearings_Whoop-_-2372272&matchtype=&pla-321137850225&cq_src=google_ads&cq_cmp=12814832524&cq_term=&cq_plac=&cq_net=g&cq_plt=gp&g

RS. (n.d.). *SKF Deep Groove Ball Bearing*. Retrieved from RS: https://uk.rs-online.com/web/p/ball-bearings/1440832?cm_mmc=UK-PLA-DS3A-_-google-_-CSS_UK_EN_Bearings_%26_Seals_Whoop-_-Ball+Bearings_Whoop-_-1440832&matchtype=&pla-299794075840&cq_src=google_ads&cq_cmp=12814832524&cq_term=&cq_plac=&cq_net=g&cq_plt=gp&gcl

RS. (n.d.). *SKF HK Needle Roller Bearing*. Retrieved from RS: https://uk.rs-online.com/web/p/roller-bearings/2092202?cm_mmc=UK-PLA-DS3A-_-google-_-CSS_UK_EN_Bearings_%26_Seals_Whoop-_-Roller+Bearings_Whoop-_-2092202&matchtype=&pla-338636918126&cq_src=google_ads&cq_cmp=12814832524&cq_term=&cq_plac=&cq_net=g&cq_plt=gp

RS. (n.d.). *SKF Spherical Roller Bearing*. Retrieved from RS: https://uk.rs-online.com/web/p/roller-bearings/0506444?cm_mmc=UK-PLA-DS3A-_-google-_-CSS_UK_EN_Bearings_%26_Seals_Whoop-_-Roller+Bearings_Whoop-_-506444&matchtype=&pla-299384902497&cq_src=google_ads&cq_cmp=12814832524&cq_term=&cq_plac=&cq_net=g&cq_plt=gp&

RYERSON. (n.d.). *Aluminum Sheet*. Retrieved from RYERSON: https://www.ryerson.com/stocklist/detail/2bbf264e-f9c8-475d-a0dd-b438f94e5f06

SHIN, Y. (n.d.). *Zinc Alloy Butt Hinge*. Retrieved from YOE SHIN: https://www.tai-sam.com/CL-209-4.htm

Shutterstock. (n.d.). *Hinge doors.* Retrieved from Shutterstock: https://www.shutterstock.com/search/car-door-hinges

SLIPLO. (n.d.). *Carbon Fiber*. Retrieved from SLIPLO UNIVERSAL SKID PLATE: https://sliplo.shop/blogs/blog/carbon-fiber-vs-pvc-soft-rubber-vs-plastic-what-s-the-best-car-door-sill-protector-material

Sprockets., G. &. (n.d.). *Metric Steel Bevel Gears*. Retrieved from https://www.gearsandsprockets.co.uk/steel-bevel-gear-mod-1-1.5-1-16t-24t.html

Station, T. (n.d.). *Brass Plated Butt Hinge 75mm*. Retrieved from Tool Station: https://www.toolstation.com/brass-plated-butt-hinge/p66967

Stevens, M. (2022, 01 25). *13 Different Types of Car Doors*. Retrieved from Car Treatments. : https://cartreatments.com/types-of-car-doors/

Store, M. (n.d.). *Mild Steel Sheet*. Retrieved from The Metal Store: https://www.themetalstore.co.uk/products/0-8mm-thick-mild-steel-sheet?utm_source=google&utm_medium=product_feed&utm_campaign=products&gclid=CjwKCAiA0cyfBhBREiwAAtStHEOJ5Z9l9c_zaHiSWsPkgd6t9prbhZFb1bepGBhiQklvKxCIUdLbxxoCRFIQAvD_BwE

Swadeology. (nd, nd nd). *Swadeology*. Retrieved from Swadeology: https://swadeology.com/2012/01/do-you-know-where-ive-been-today-part-2/dsc_3194/

Thomas., I. (n.d.). *All About Rack and Pinion Gears - What They Are and How They Work*. Retrieved from https://www.thomasnet.com/articles/machinery-tools-supplies/rack-and-pinion-gears/

UK, R. (n.d.). *Southco Stainless Steel Concealed Hinge, Screw, Weld-on Fixing 38.5mm x 76mm x 8.4mm*. Retrieved from RS UK: https://uk.rs-online.com/web/p/hinges/4474994?cm_mmc=UK-PLA-DS3A-_-google-_-CSS_UK_EN_Security_%26_Ironmongery_Whoop-_-Hinges_Whoop+(2)-_-4474994&matchtype=&pla-339196811503&cq_src=google_ads&cq_cmp=10914490521&cq_term=&cq_plac=&cq_net=g&cq_plt=gp&gclid=C

23. Appendix

23.1. Appendix 1: Material Comparison Graphs used to select materials.

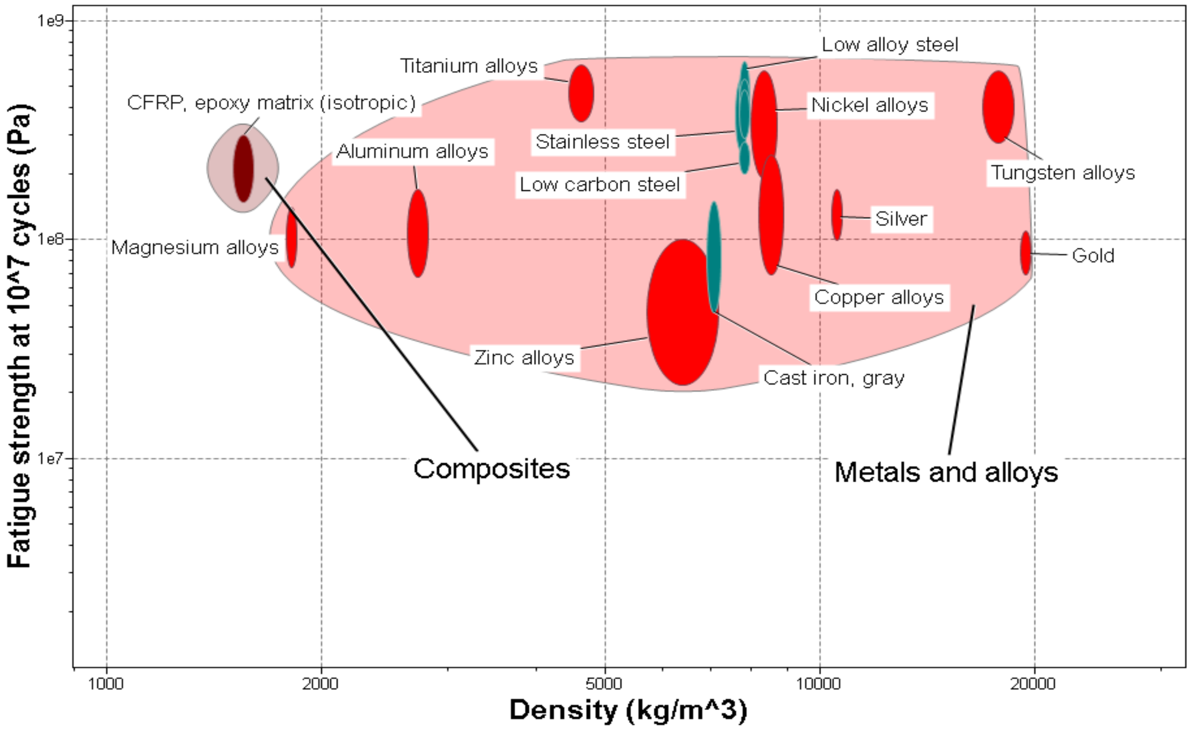


Figure 59: *Fracture Toughness Vs Density graph of different Metals and Composites.* ***[GRANTA EDUPACK]***

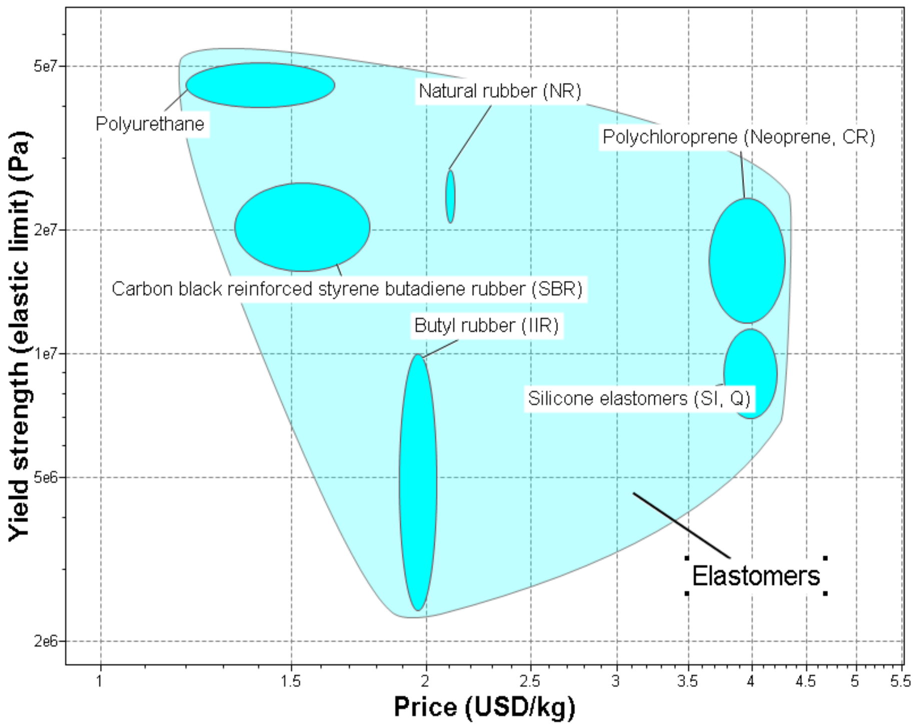


Figure 60: *Yield Strength Vs Price of Elastomers.* ***[GRANTA EDUPACK]***

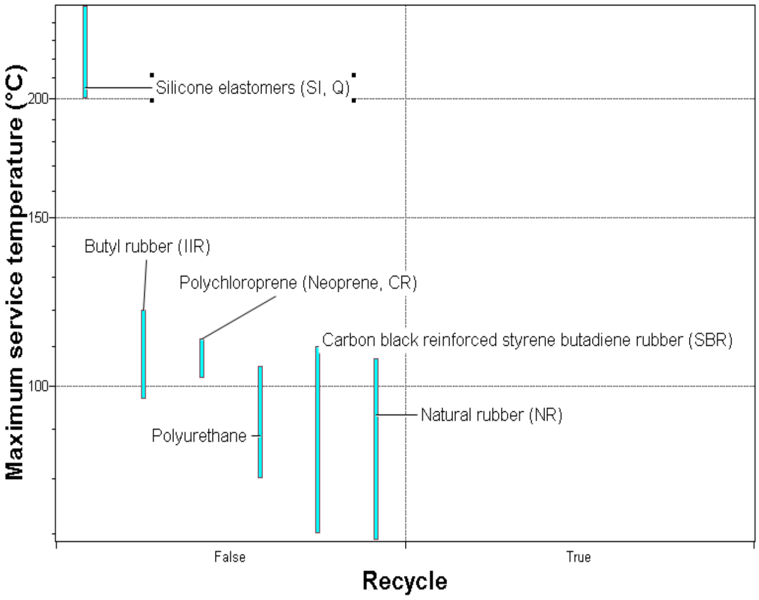


Figure 61; *Maximum temperature Vs Recycle of various Elastomers*. ***[GRANTA EDUPACK]***

23.2. Appendix 2: Exploded View of Hinge and Linear Actuator

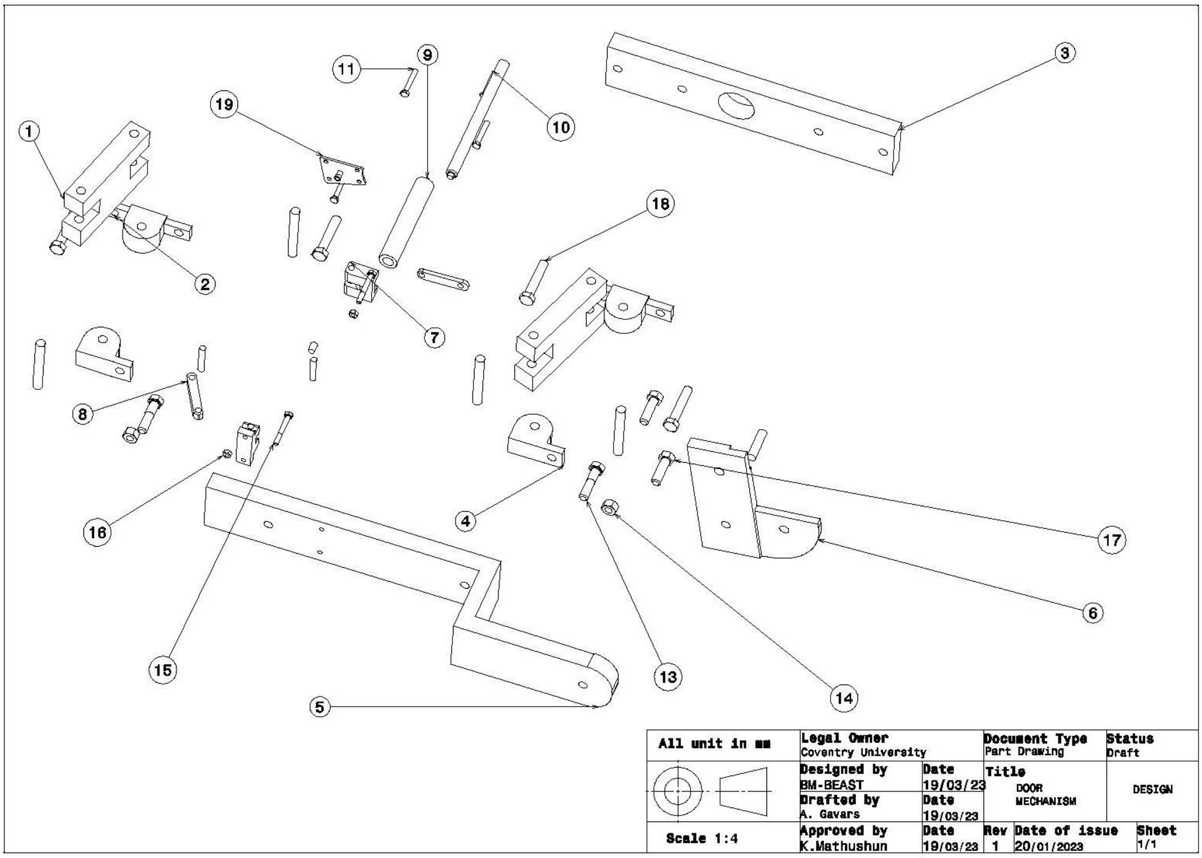


Figure 62: *Figure showing the exploded view of hinge and small linear actuator.*

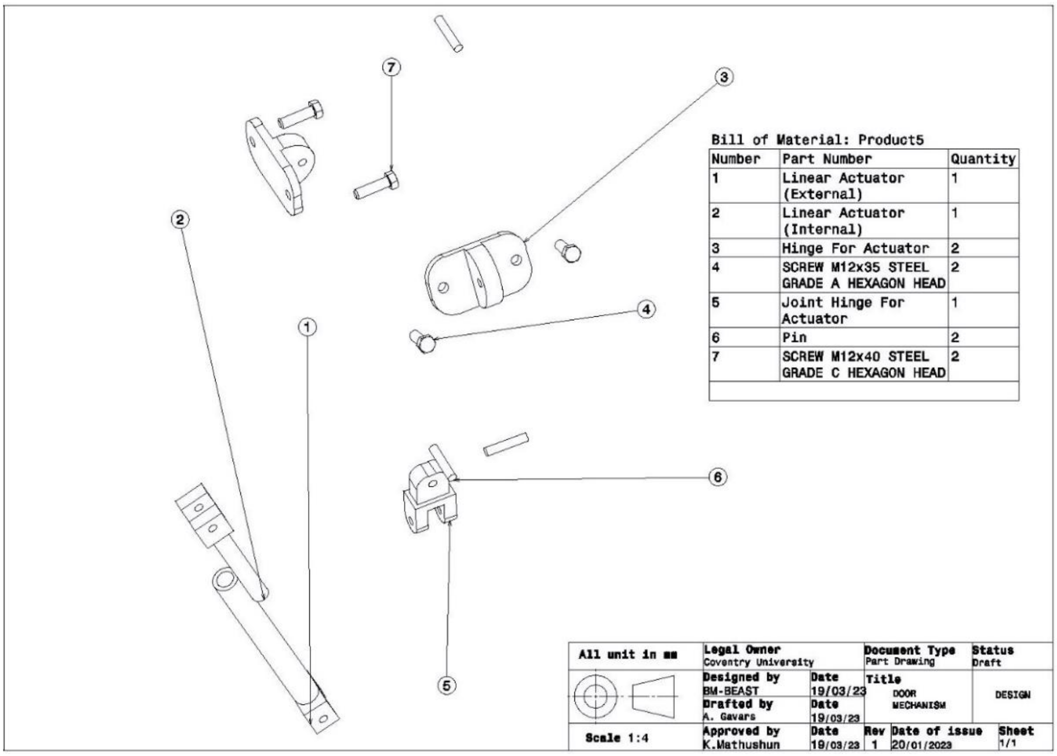


Figure 63*: Figure showing the exploded view of bigger linear actuator.*

Bill of Material: Car Door Hinge

Number	Part Number	Quantity
1	Linkage	2
2	Hinge For Linkage	2
3	Base Plate For Hinge	1
4	Linkage Hinge	2
5	Plate for Linkage	1
6	Hinge Arm	1
7	Hinge For Linear Actuator	2
8	Oval Plate for Linear Actuator Connection	2
9	Linear Actuator (External)	1
10	Linear Actuator (Internal)	1
11	Pins	4
12	SCREW M6x40 STEEL GRADE A HEXAGON HEAD	4
13	BOLT M12x50 STEEL GRADE A HEXAGON HEAD	2
14	NUT M12 STEEL GRADE A HEXAGON	2
15	BOLT M6x50 STEEL GRADE A HEXAGON HEAD	2
16	NUT M6 STEEL GRADE A HEXAGON	2
17	SCREW M12x40 STEEL GRADE C HEXAGON HEAD	4
18	SCREW M12x60 STEEL GRADE C HEXAGON HEAD	4
19	Linear Actuator Base	1

Figure 64*: Figure showing Bill of Material.*

23.3. Appendix 3: Tables and Charts used to create DFM.

(**Component:** Front arm/Door Hinge**)**

Table 11: *Waste Coefficient table (Wc) with marked values for all 10 components.*

Shape Classification \ Process	AM	CCEM	CDF	CEP	CF	CH	CMC	CNC	CPM	GDC	HCEM	IC	IM	MM	PDC	PM	SM	SC	SMW	VF
A1	1.6	1	1.1	1	1	1	1.1	1.6	1	1	1	1	1.1	1.6	1	1	1	1.1		1
A2	2	1	1.1	1.1	1	1	1.1	2	1.1	1.1	1	1	1.1	2	1.1	1	1.1	1.1		1.1
A3	2.5	1.5	1.2		1	1	1.2	2.5	1.1	1.1	1.5	1.1	1.1	2.5	1.1	1	1.1	1.2		1.1
A4	3	2	1.2				1.3	3	1.2	1.2	2	1.1	1.1	3	1.2	1	1.2	1.3		1.2
A5	4	3	1.3				1.4	4	1.3	1.3	3	1.2	1.2	4	1.3	1.2	1.3	1.4		1.3
B1	1.7	1	1.1	1	1	1	1.1	1.7	1	1	1	1	1.1	1.7	1	1	1	1.1		1
B2	2.2	1	1.1	1.1	1	1	1.1	2.2	1.1	1.1	1	1	1.1	2.2	1.1	1	1.1	1.1		1.1
B3	2.8	1.5	1.2		1	1	1.2	2.8	1.1	1.1	1.5	1.1	1.1	2.8	1.1	1	1.1	1.2		1.1
B4	4	2	1.2				1.3	4	1.1	1.2	2	1.1	1.1	4	1.2	1	1.2	1.3		1.1
B5	6	3	1.3				1.4	6	1.2	1.3	3	1.2	1.2	6	1.3	1.2	1.3	1.4		1.2
C1	1.8	1	1.1	1	1	1	1.1	1.8	1	1	1	1	1.1	1.8	1.1	1	1.1	1.1	1.2	1
C2	2.4	1	1.1	1.1	1	1	1.2	2.4	1.1	1.1	1	1	1.1	2.4	1.1	1	1.1	1.2	1.2	1.1
C3	4	2	1.1		1	1	1.3	4	1.1	1.1	2	1.1	1.1	4	1.1	1	1.1	1.3	1.4	1.1
C4	6	3	1.2				1.4	6	1.1	1.2	3	1.1	1.2	6	1.2	1	1.2	1.4	1.5	1.1
C5	8	4	1.3				1.6	8	1.2	1.3	4	1.2	1.3	8	1.3	1.2	1.3	1.6	1.6	1.2

Table 12: *Relative cost data materials mentioned in table(), material processing sustainability (C_{mp}).*

Material \ Process	AM	CCEM	CDF	CEP	CF	CH	CM2.5	CM5	CMC	CNC	CPM	GDC	HCEM	IC	IM	MM	PDC	PM	SM	SC	SMW	VF
Cast Iron	1.2						1	1	1	1.2				1		1.2		1.6	1	1		
Low Carbon Steel	1.4	1.3	1		1.3	1.3	1	1	1.2	1.4			1.3	1		1.4		1.2	1.2	1.2	1.2	
Alloy Steel	2.5	2	2		2	2	1	1	1.3	2.5			2	1		2.5		1.1	1.3	1.3	1.5	
Stainless Steel	4	2	2		2	2	1	1	1.5	4			2	1		4		1.1	1.5	1.5	1.5	
Copper Alloy	1.1	1.1	1		1	1			1	1.1			1	1		1.1	3	1	1	1	1	
Aluminium Alloy	1	1.1	1		1	1			1	1		1.5	1.1	1		1	1.5	1	1	1	1	
Zinc Alloy	1.1	1	1		1	1			1	1.1		1.2	1	1		1.1	1.2	1	1	1	1	
Thermoplastic	1.1			1						1.1	1.2				1	1.1						1
Thermoset	1.2			1.2						1.2	1				1	1.2						
Elastomer	1.1			1.5						1.1	1.5				1.5	1.1						

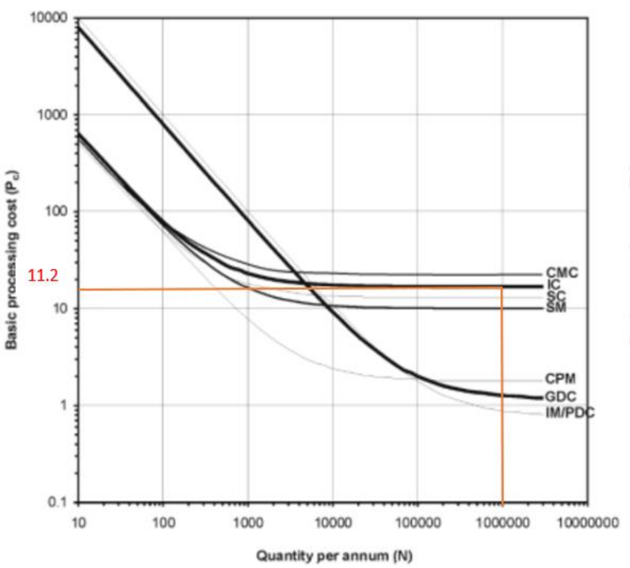


Figure 65: *Basic Processing Cost.*

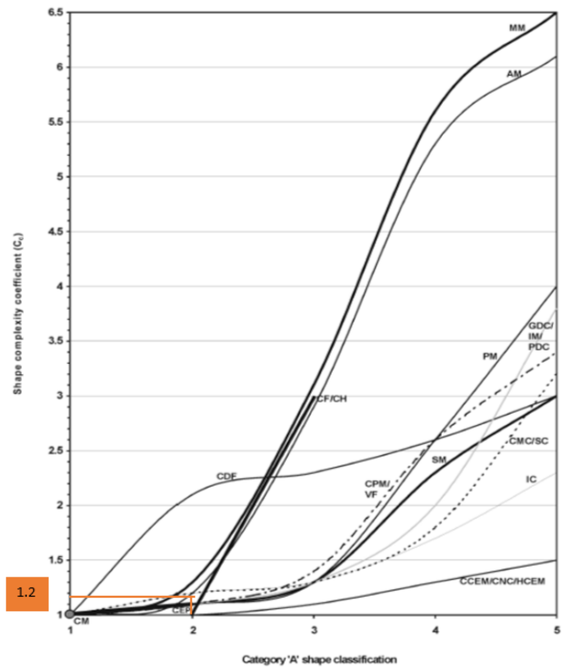


Figure 66: *Geometric Complexity Graph index for AM (C_c).*

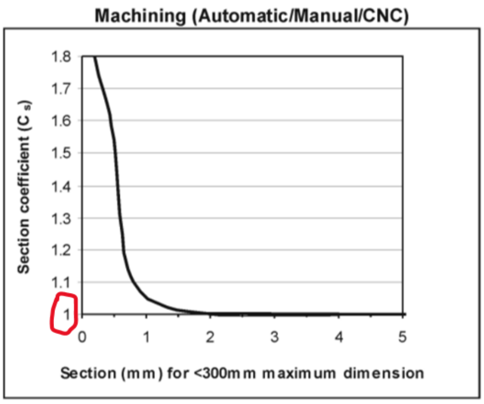


Figure 67: *Coefficient Graph for AM (C_S).*

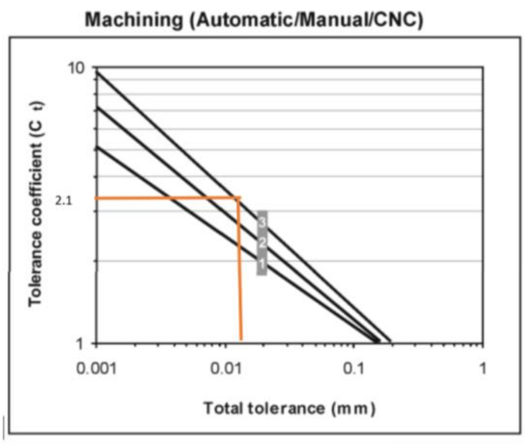


Figure 68*: Tolerance Coefficient Graph (Ct).*

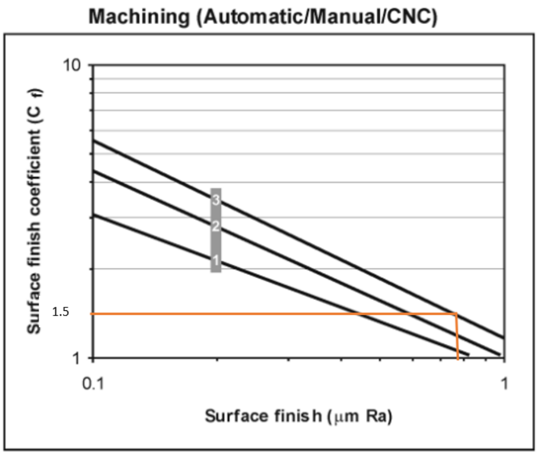


Figure 69*: Surface Finish Coefficient for AM (C_f).*

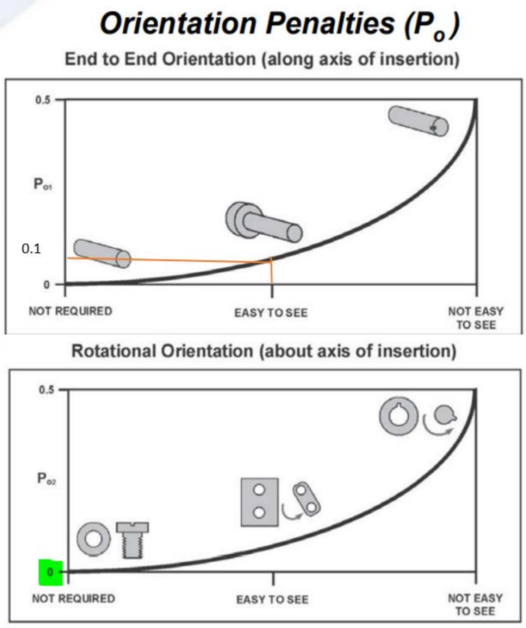
23.4. Appendix 4: Tables and Charts used to create DFA.

Basic Component Handling Indices (A_h) (select one only)

Component Handling Characteristic	Index (A_h)
One hand only	1
Very small (aids/tools)	1.5
Large and/or heavy (two hands/tools)	1.5
Very large and/or very heavy (two people/hoist)	3

General Handling Penalties (P_g)

Component Handling Sensitivity	Index (P_g)
Fragile	0.4
Flexible	0.6
Adherent	0.5
Tangle/severely tangle	0.8/1.5
Severely nest	0.7
Sharp/abrasive	0.3
Hot/contaminated	0.5
Thin (gripping problem)	0.2
None of the above	0



Assembly Process	Index (A_f)
Insertion only	1
Snap fit	1.3
Screw fastener	4
Rivet fastener	2.5
Clip fastener (plastic bending)	3
Placement in work holder (P_f and P_a usually not required)	1

Additional Assembly Process	Index (P_a)
Additional screw running	4
Later plastic deformation	3
Soldering/brazing/gas welding	6
Adhesive bonding/spot welding	5
Reorientation	1.5
Liquid/gas fill or empty	5
Set/test/measure/other [easy/difficult]	1.5/7.5

Figure 70: *Design for Assembly criteria for handling and penalties.*

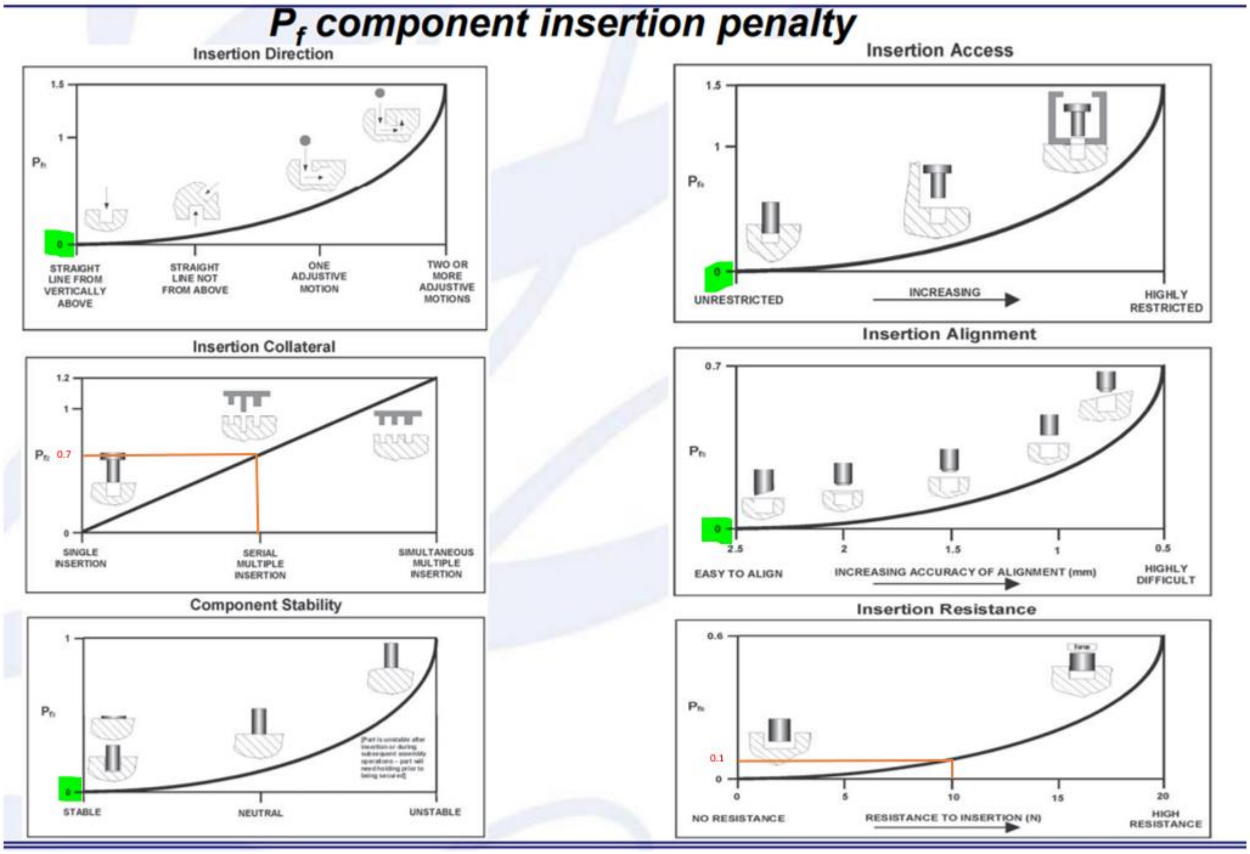


Figure 71: *Showing the values for component insertion penalty.*

23.5. Appendix 5: AHP, Design selection criteria

Intensity of importance	Definition	Explanation on an absolute scale
1	*Equal importance*	Two activities contribute equally to the objective
3	*Moderate importance of one another*	Experience and judgment strongly favour one activity over another
5	*Essential or Strong importance*	Experience and judgement strongly favour one activity over another
7	*Very strong importance*	An activity is strongly favoured and its dominance demons t rated in practice
9	*Extreme importance*	The evidence favouring one activity over another is of the highest possible order or affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals	If activity ***i*** has one of the above numbers assigned to it when compared with activity ***j***, then ***j*** has the reciprocal value when compared with ***i***	
Rationales	Ratios arising from the scale	If consistency were to be forced by obtaining ***n*** numerical values to span the matrix

Figure 72: *Selection criteria's to develop AHP.*

Table 13: *Tables with the AHP values obtained.*

CM1	Cost	Convenience	Manufacturability	Performance
Cost	1	1/3	3	1/3
Convenience	3	1	2	2
Manufacturability	1/3	1/2	1	1
Performance	3	1/2	1	1
SUM	***7.333***	***2.333***	***7.000***	***4.333***

	Cost	Convenience	Manufacturability	Performance	**PRIORITY VECTOR**
Cost	0.136	0.143	0.429	0.077	0.196
Convenience	0.409	0.429	0.286	0.462	0.396
Manufacturability	0.045	0.214	0.143	0.231	0.158
Performance	0.409	0.214	0.143	0.231	0.249

CM2		
Cost	*Production Cost*	*Maintenance Cost*
Production Cost	1	3
Maintenance Cost	1/3	1
SUM	*1.3333*	*4.0000*

Normalized Comparison Matrix

Cost	*Production Cost*	*Maintenance Cost*		**Priority Vector**
Production Cost	0.750	0.750		0.750
Maintenance Cost	0.250	0.250		0.250

CM3		
Convenience	*Easy to Handle*	*Safe to Operate*
Easy to Handle	1	1/5
Safe to Operate	5	1
SUM	*6.0000*	*1.2000*

Normalized Comparison Matrix

Convenience	*Easy to Handle*	*Safe to Operate*		**Priority Vector**
Easy to Handle	0.167	0.167		0.167
Safe to Operate	0.833	0.833		0.833

CM4			
Manufacturability	*Durability*	*Easy assembly*	*Low part count*
Durability	1	3	5
Easy assembly	1/3	1	2
Low part count	1/5	1/2	1
SUM	*1.5333*	*4.5000*	*8.0000*

Normalized Comparison Matrix

Manufacturability	*Durability*	*Easy assembly*	*Low part count*		**Priority Vector**
Durability	0.652	0.667	0.625		0.648
Easy assembly	0.217	0.222	0.250		0.230
Low part count	0.130	0.111	0.125		0.122

CM5		
Performance	*Energy Efficiency*	*Speed*
Energy Efficiency	1	3
Speed	1/3	1
SUM	*1.3333*	*4.0000*

Normalized Comparison Matrix

Performance	*Energy Efficiency*	*Speed*		**Priority Vector**
Energy Efficiency	0.750	0.750		0.750
Speed	0.250	0.250		0.250

CM6			
Low Maintenance Cost	*Design A*	*Design B*	*Design C*
Design A	1	1/3	3
Design B	3	1	1/2
Design C	1/3	2	1
SUM	*4.3333*	*3.3333*	*4.5000*

Normalized Comparison Matrix

Low Maintenance Cost	*Design A*	*Design B*	*Design C*		**Priority Vector**
Design A	0.231	0.100	0.667		0.332
Design B	0.692	0.300	0.111		0.368
Design C	0.077	0.600	0.222		0.300

CM7			
Low Production Cost	*Design A*	*Design B*	*Design C*
Design A	1	1/2	2
Design B	2	1	1/2
Design C	1/2	2	1
SUM	*3.5000*	*3.5000*	*3.5000*

Normalized Comparison Matrix

Low Production Cost	*Design A*	*Design B*	*Design C*		**Priority Vector**
Design A	0.286	0.143	0.571		0.333
Design B	0.571	0.286	0.143		0.333
Design C	0.143	0.571	0.286		0.333

CM8			
Easy to Handle	*Design A*	*Design B*	*Design C*
Design A	1	3	2
Design B	1/3	1	1/2
Design C	1/2	2	1
SUM	*1.8333*	*6.0000*	*3.5000*

Normalized Comparison Matrix

Easy to Handle	*Design A*	*Design B*	*Design C*	**Priority Vector**
Design A	0.545	0.500	0.571	0.539
Design B	0.182	0.167	0.143	0.164
Design C	0.273	0.333	0.286	0.297

CM9			
Safe to Operate	*Design A*	*Design B*	*Design C*
Design A	1	3	3
Design B	1/3	1	2
Design C	1/3	1/2	1
SUM	*1.6667*	*4.5000*	*6.0000*

Normalized Comparison Matrix

Safe to Operate	*Design A*	*Design B*	*Design C*	**Priority Vector**
Design A	0.600	0.667	0.500	0.589
Design B	0.200	0.222	0.333	0.252
Design C	0.200	0.111	0.167	0.159

CM10			
Durability	*Design A*	*Design B*	*Design C*
Design A	1	3	2
Design B	1/3	1	3
Design C	1/2	1/3	1
SUM	*1.8333*	*4.3333*	*6.0000*

Normalized Comparison Matrix

Durability	*Design A*	*Design B*	*Design C*	**Priority Vector**
Design A	0.545	0.692	0.333	0.524
Design B	0.182	0.231	0.500	0.304
Design C	0.273	0.077	0.167	0.172

CM11			
Easy Assembly	*Design A*	*Design B*	*Design C*
Design A	1	1/3	2
Design B	3	1	1/2
Design C	1/2	2	1
SUM	*4.5000*	*3.3333*	*3.5000*

Normalized Comparison Matrix

Easy Assembly	*Design A*	*Design B*	*Design C*		**Priority Vector**
Design A	0.222	0.100	0.571		0.298
Design B	0.667	0.300	0.143		0.370
Design C	0.111	0.600	0.286		0.332

CM12			
Low part count	*Design A*	*Design B*	*Design C*
Design A	1	1/3	2
Design B	3	1	1/2
Design C	1/2	2	1
SUM	*4.5000*	*3.3333*	*3.5000*

Normalized Comparison Matrix

Low part count	*Design A*	*Design B*	*Design C*		**Priority Vector**
Design A	0.222	0.100	0.571		0.298
Design B	0.667	0.300	0.143		0.370
Design C	0.111	0.600	0.286		0.332

CM13			
Energy Efficiency	*Design A*	*Design B*	*Design C*
Design A	1	3	2
Design B	1/3	1	4
Design C	1/2	1/4	1
SUM	*1.8333*	*4.2500*	*7.0000*

Normalized Comparison Matrix

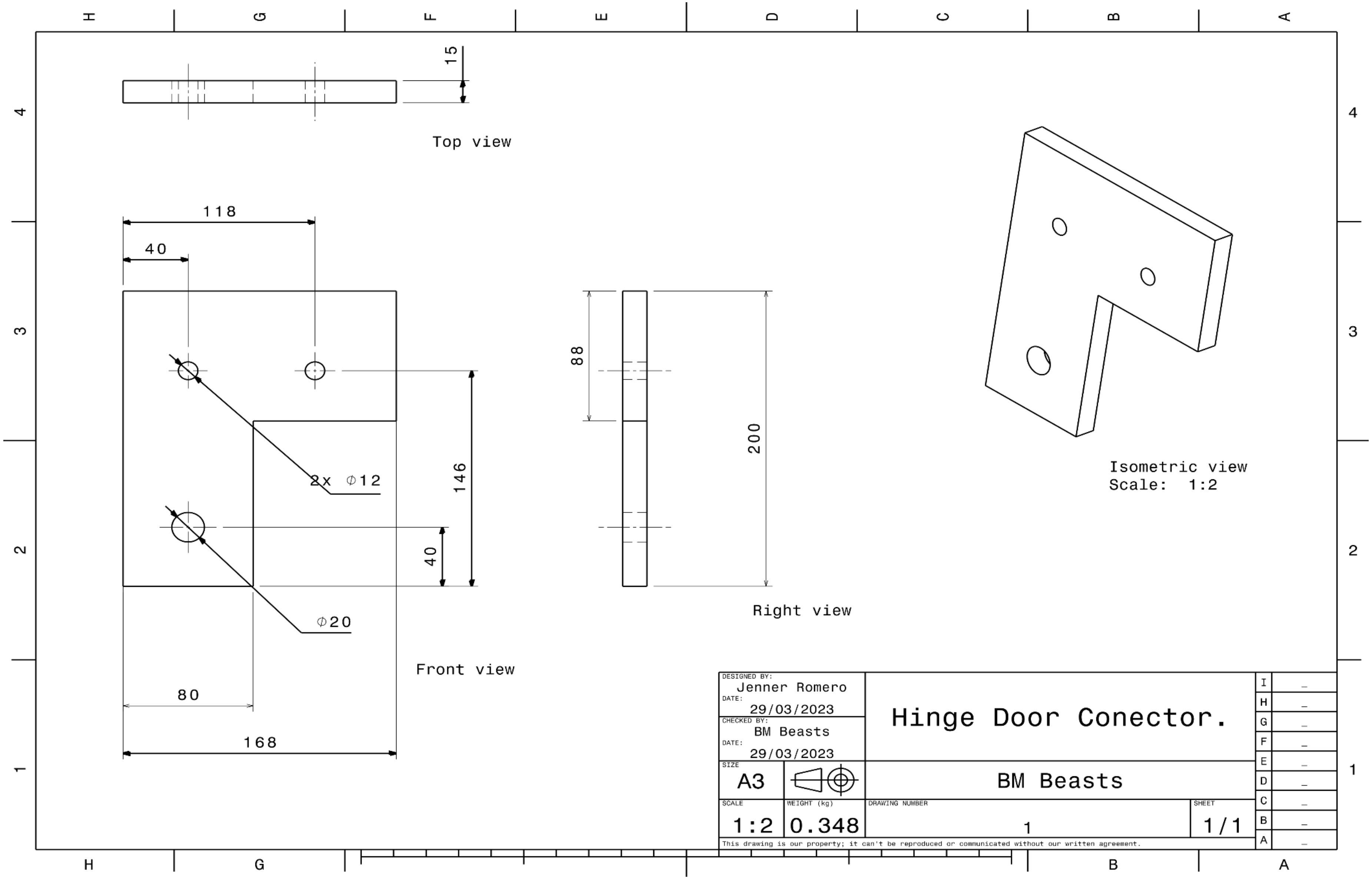
Energy Efficiency	*Design A*	*Design B*	*Design C*	**Priority Vector**
Design A	0.545	0.706	0.286	0.512
Design B	0.182	0.235	0.571	0.330
Design C	0.273	0.059	0.143	0.158

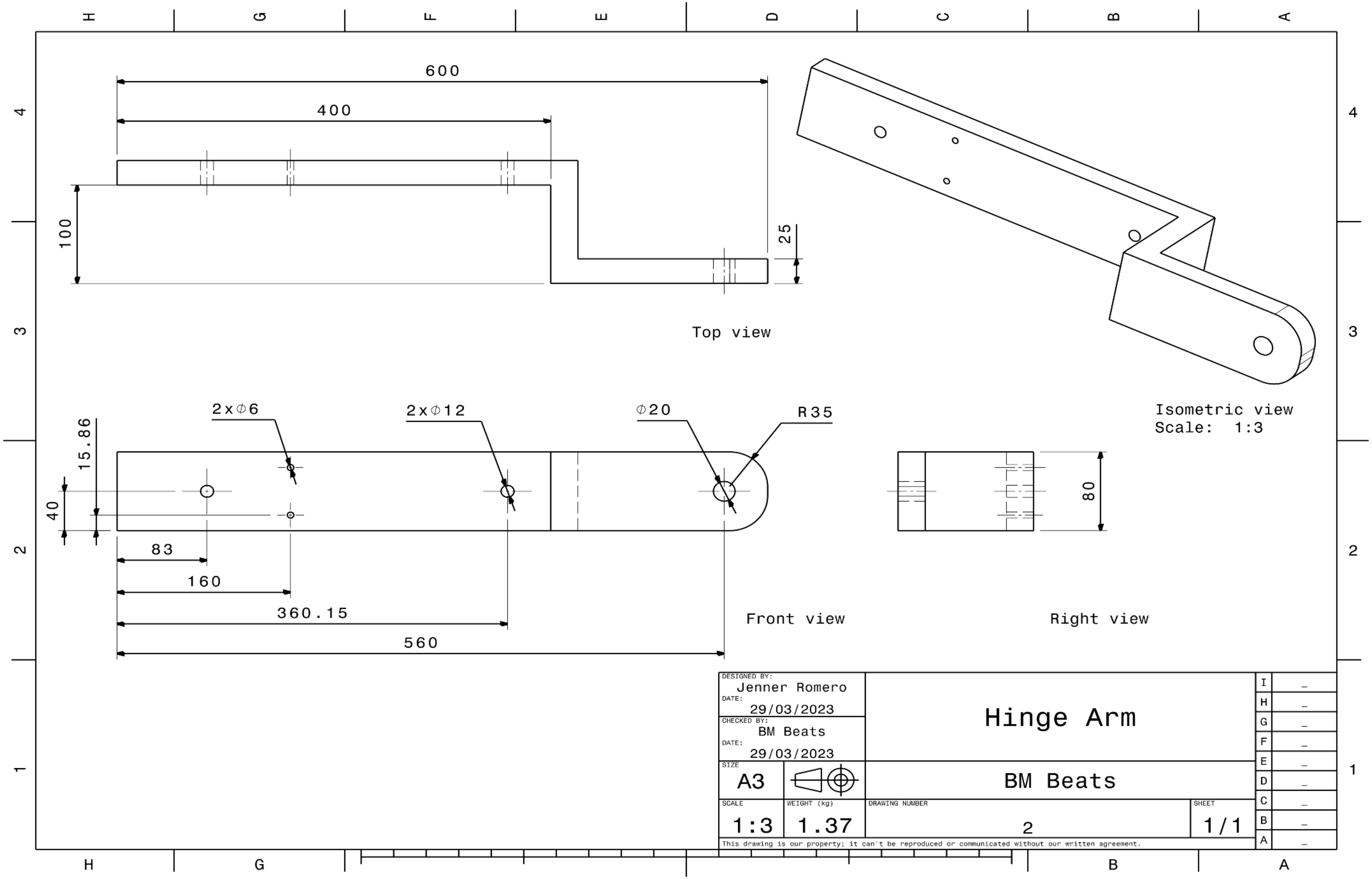
CM14			
Speed	*Design A*	*Design B*	*Design C*
Design A	1	4	3
Design B	1/4	1	5
Design C	1/3	1/5	1
SUM	*1.5833*	*5.2000*	*9.0000*

Normalized Comparison Matrix

Speed	*Design A*	*Design B*	*Design C*	**Priority Vector**
Design A	0.632	0.769	0.333	0.578
Design B	0.158	0.192	0.556	0.302
Design C	0.211	0.038	0.111	0.120

23.6. Technical Drawing of Hinge Components


15
Top view
118
40
88
200
146
40
2x ⌀12
⌀20
80
168
Front view
Right view
Isometric view
Scale: 1:2
DESIGNED BY:
Jenner Romero
DATE:
29/03/2023
CHECKED BY:
BM Beasts
DATE:
29/03/2023
Hinge Door Conector.
SIZE
A3
BM Beasts
SCALE
1:2
WEIGHT (kg)
0.348
DRAWING NUMBER
1
SHEET
1/1
This drawing is our property; it can't be reproduced or communicated without our written agreement.


600
400
100
25
Top view
Isometric view
Scale: 1:3
2x⌀6
2x⌀12
⌀20
R35
15.86
40
83
160
360.15
560
80
Front view
Right view
DESIGNED BY:
Jenner Romero
DATE:
29/03/2023
CHECKED BY:
BM Beats
DATE:
29/03/2023
Hinge Arm
SIZE
A3
BM Beats
SCALE
1:3
WEIGHT (kg)
1.37
DRAWING NUMBER
2
SHEET
1/1
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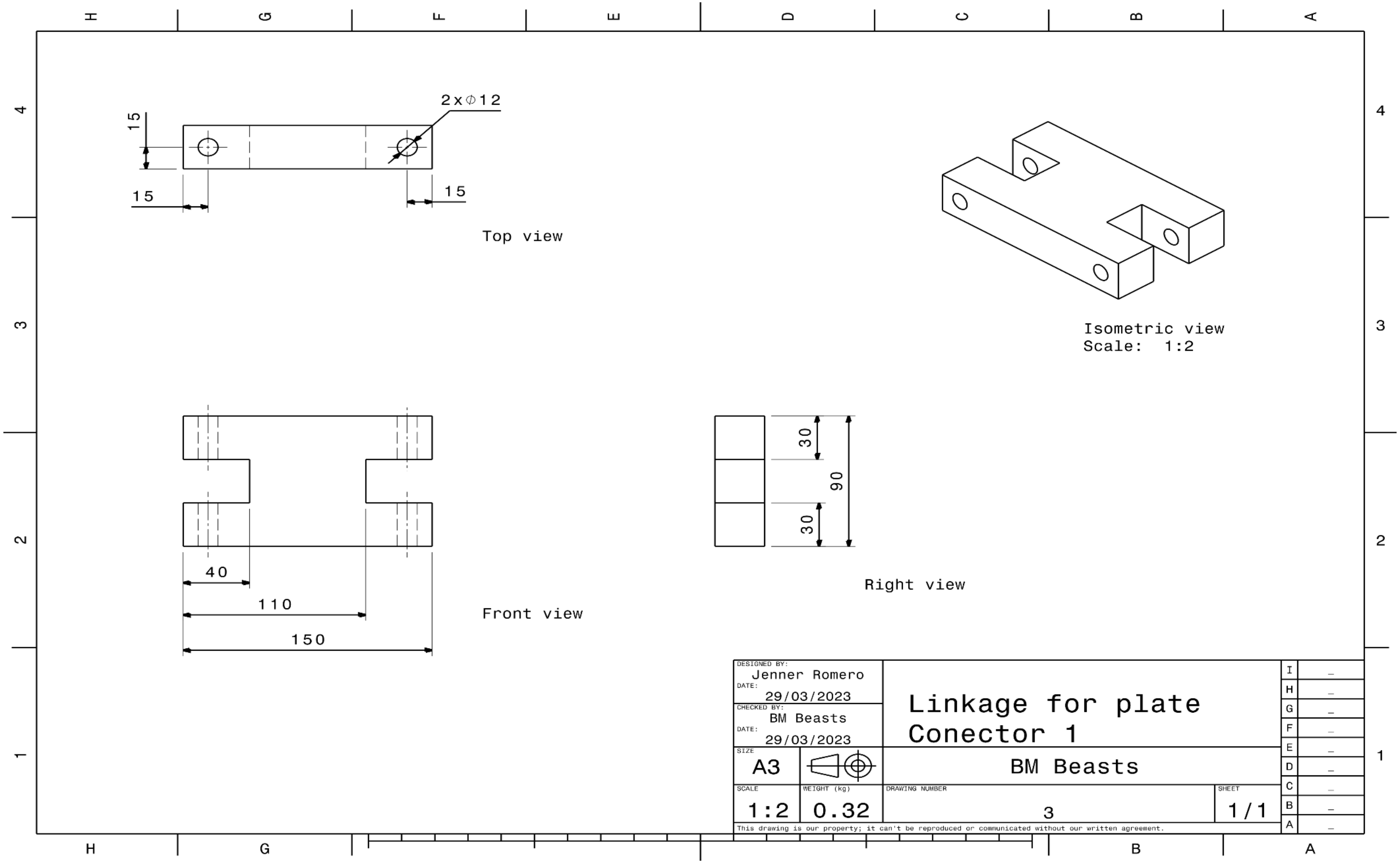
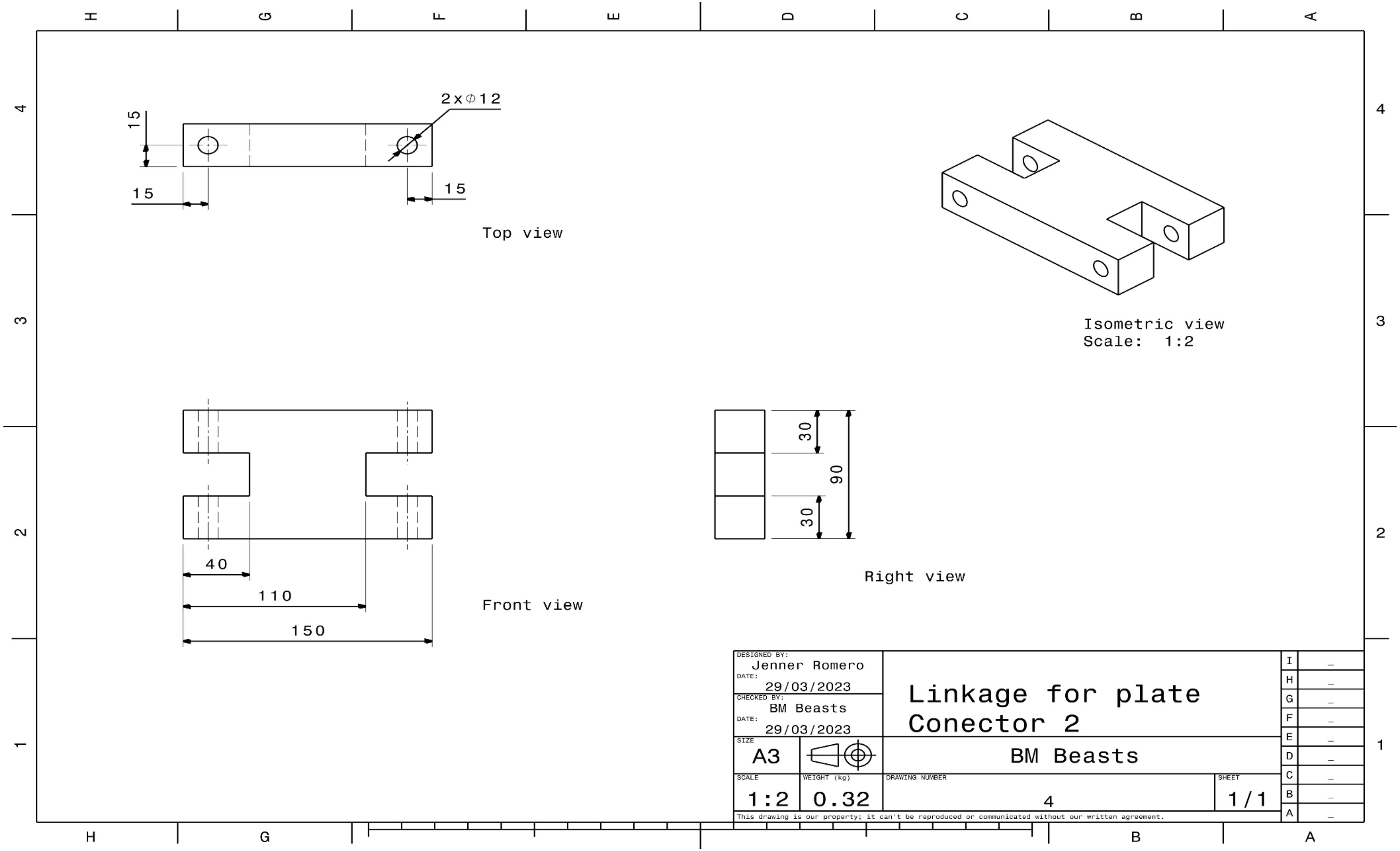
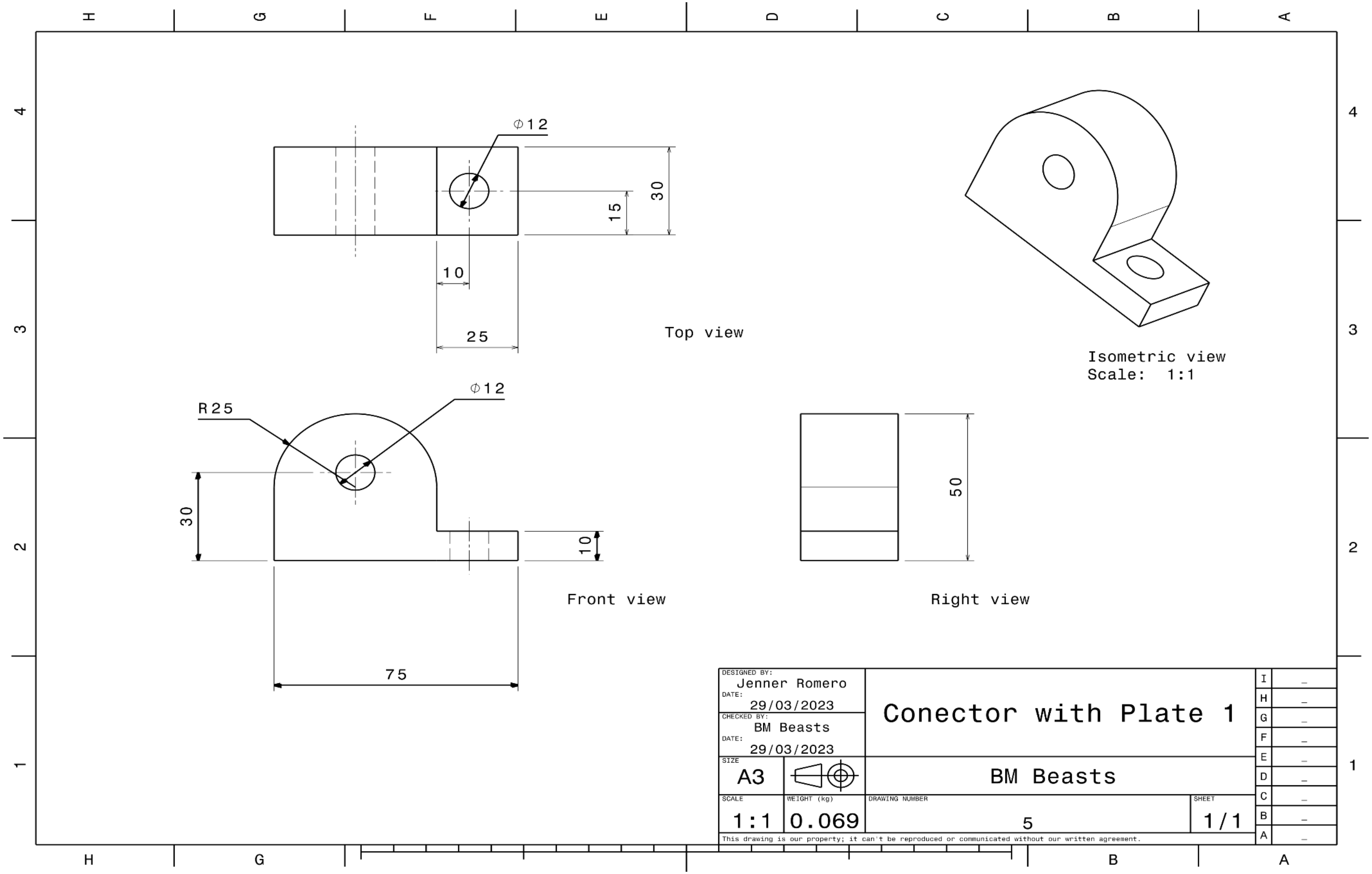

2xΦ12
15
15
15
Top view
Isometric view
Scale: 1:2
30
90
30
Right view
40
110
150
Front view
DESIGNED BY:
Jenner Romero
DATE:
29/03/2023
CHECKED BY:
BM Beasts
DATE:
29/03/2023
Linkage for plate
Conector 1
SIZE
A3
BM Beasts
SCALE
1:2
WEIGHT (kg)
0.32
DRAWING NUMBER
3
SHEET
1/1
This drawing is our property; it can't be reproduced or communicated without our written agreement.



2x∅12
15
15
15
Top view
Isometric view
Scale: 1:2
30
90
30
40
110
150
Front view
Right view
DESIGNED BY:
Jenner Romero
DATE:
29/03/2023
CHECKED BY:
BM Beasts
DATE:
29/03/2023
Linkage for plate
Conector 2
SIZE
A3
BM Beasts
SCALE
1:2
WEIGHT (kg)
0.32
DRAWING NUMBER
4
SHEET
1/1
This drawing is our property; it can't be reproduced or communicated without our written agreement.



Φ12
30
15
10
25
Top view
Isometric view
Scale: 1:1
R25
Φ12
30
10
75
50
Front view
Right view
DESIGNED BY:
Jenner Romero
DATE:
29/03/2023
CHECKED BY:
BM Beasts
DATE:
29/03/2023
Conector with Plate 1
SIZE
A3
BM Beasts
SCALE
1:1
WEIGHT (kg)
0.069
DRAWING NUMBER
5
SHEET
1/1
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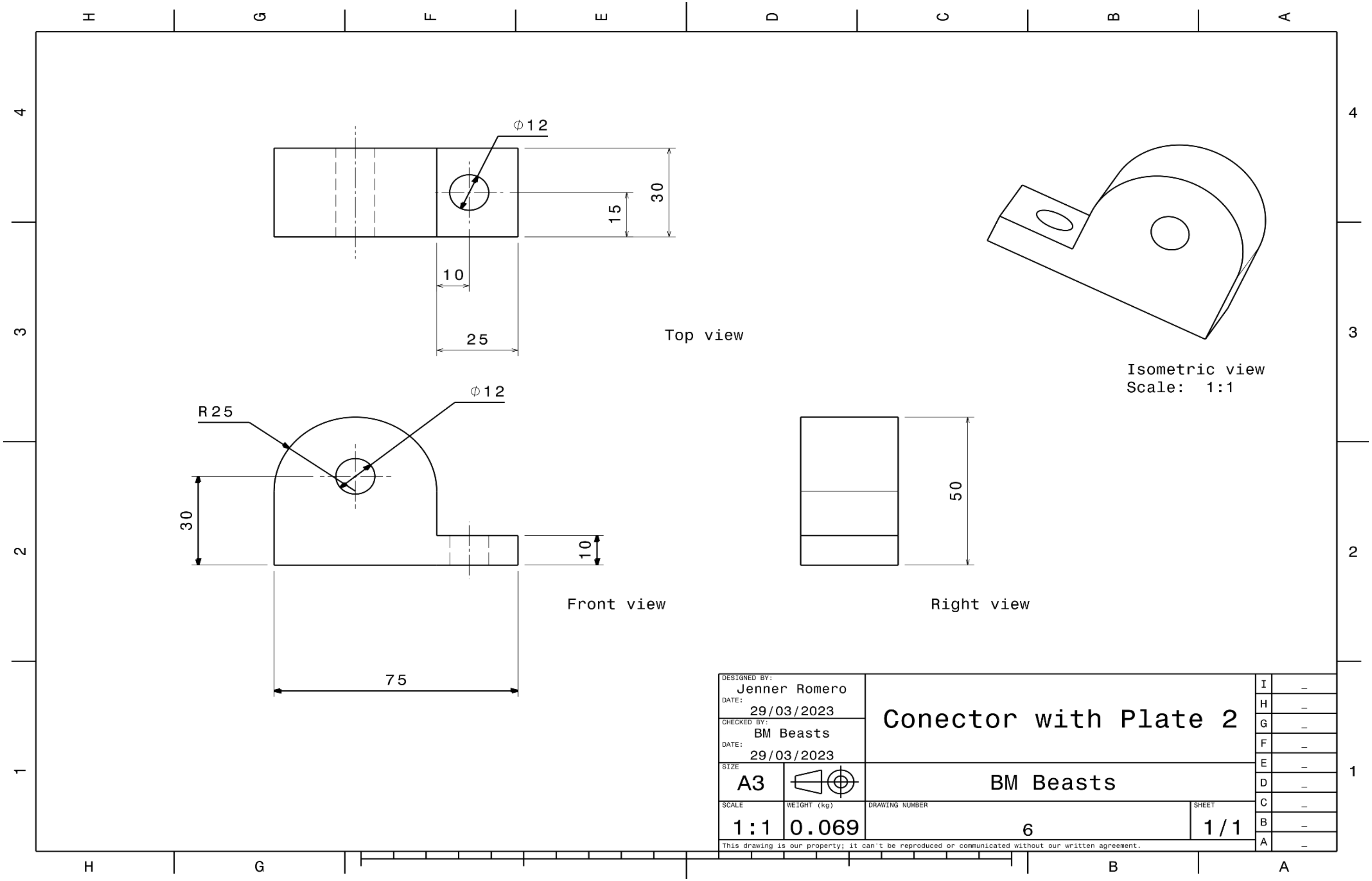
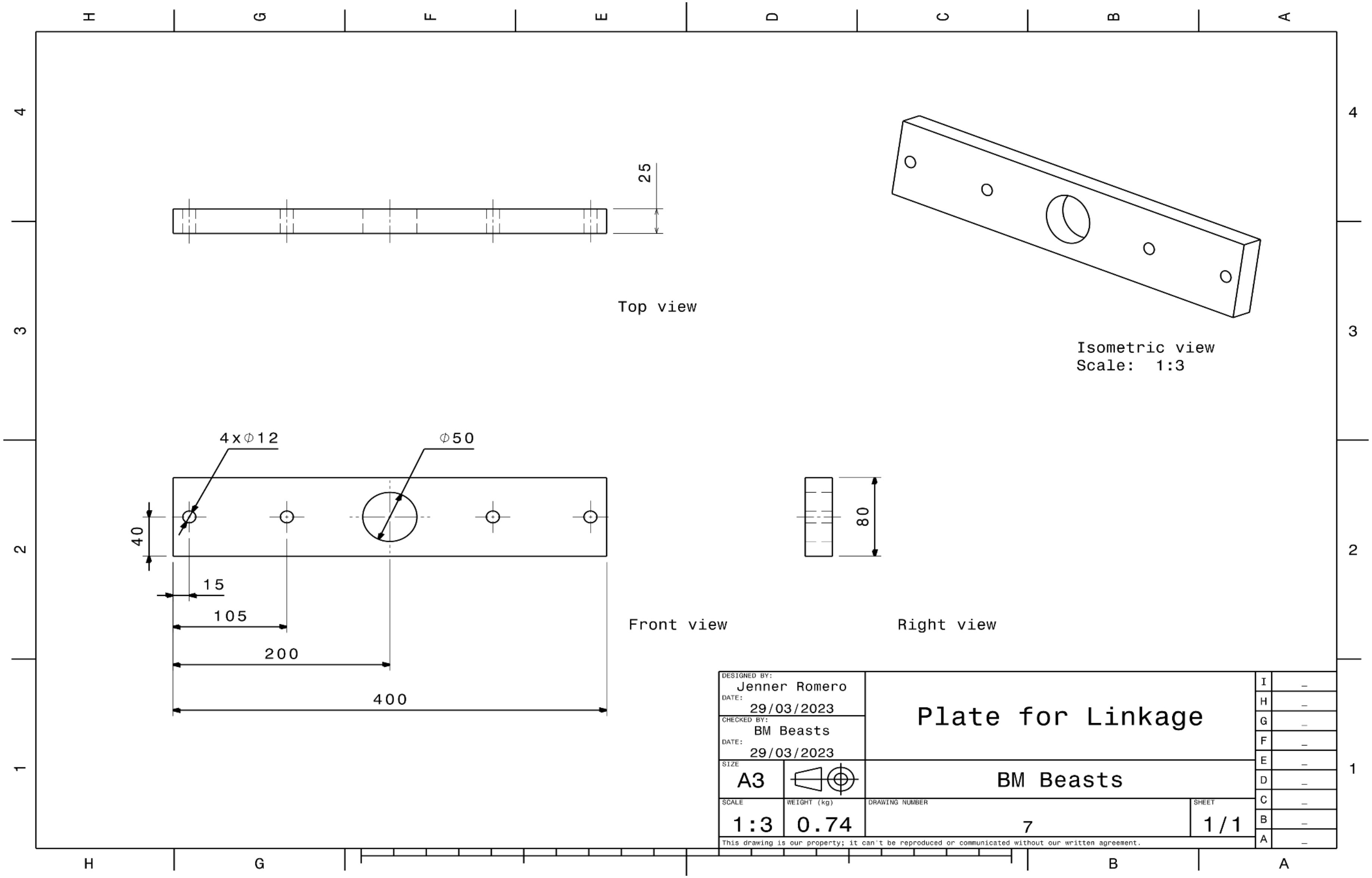
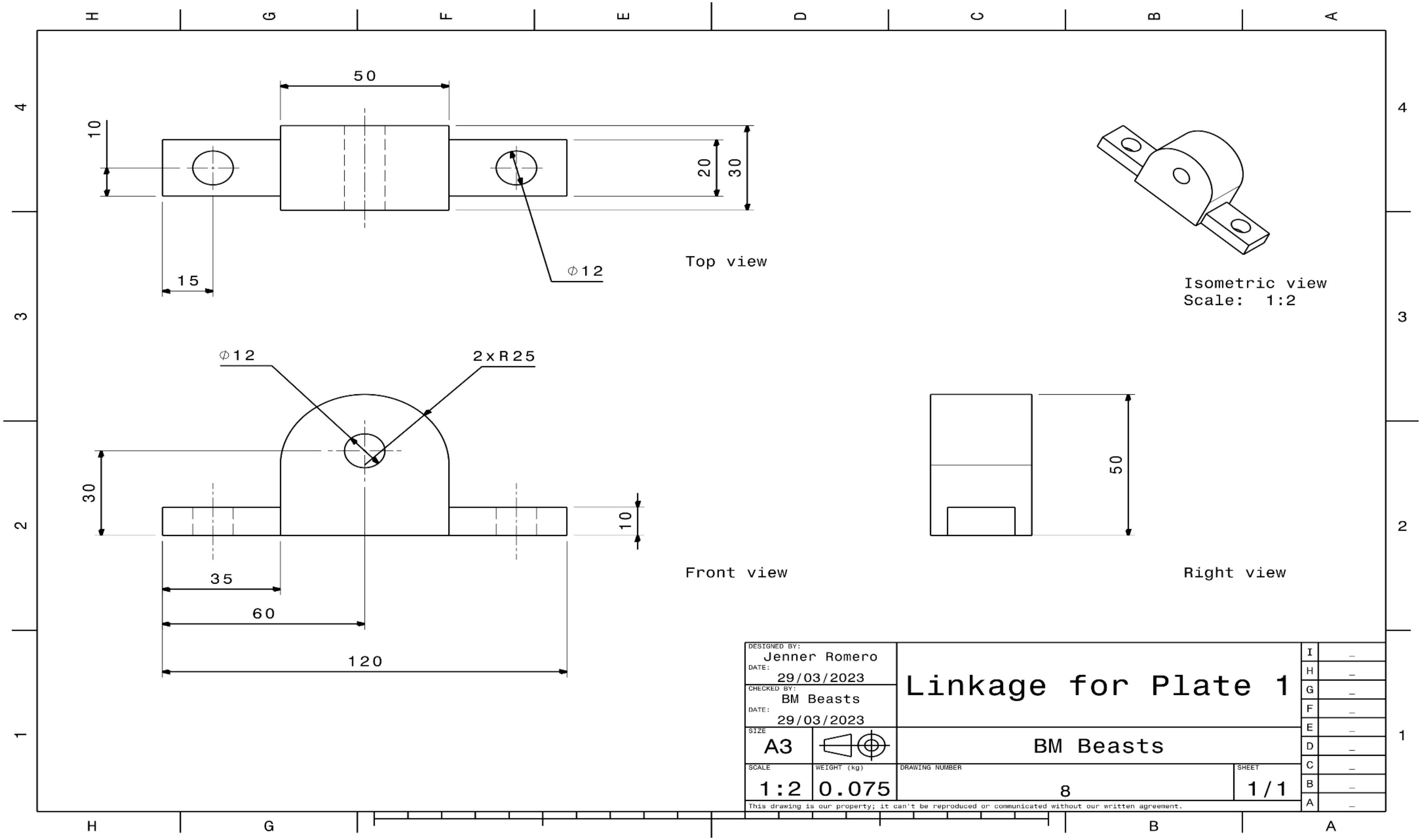


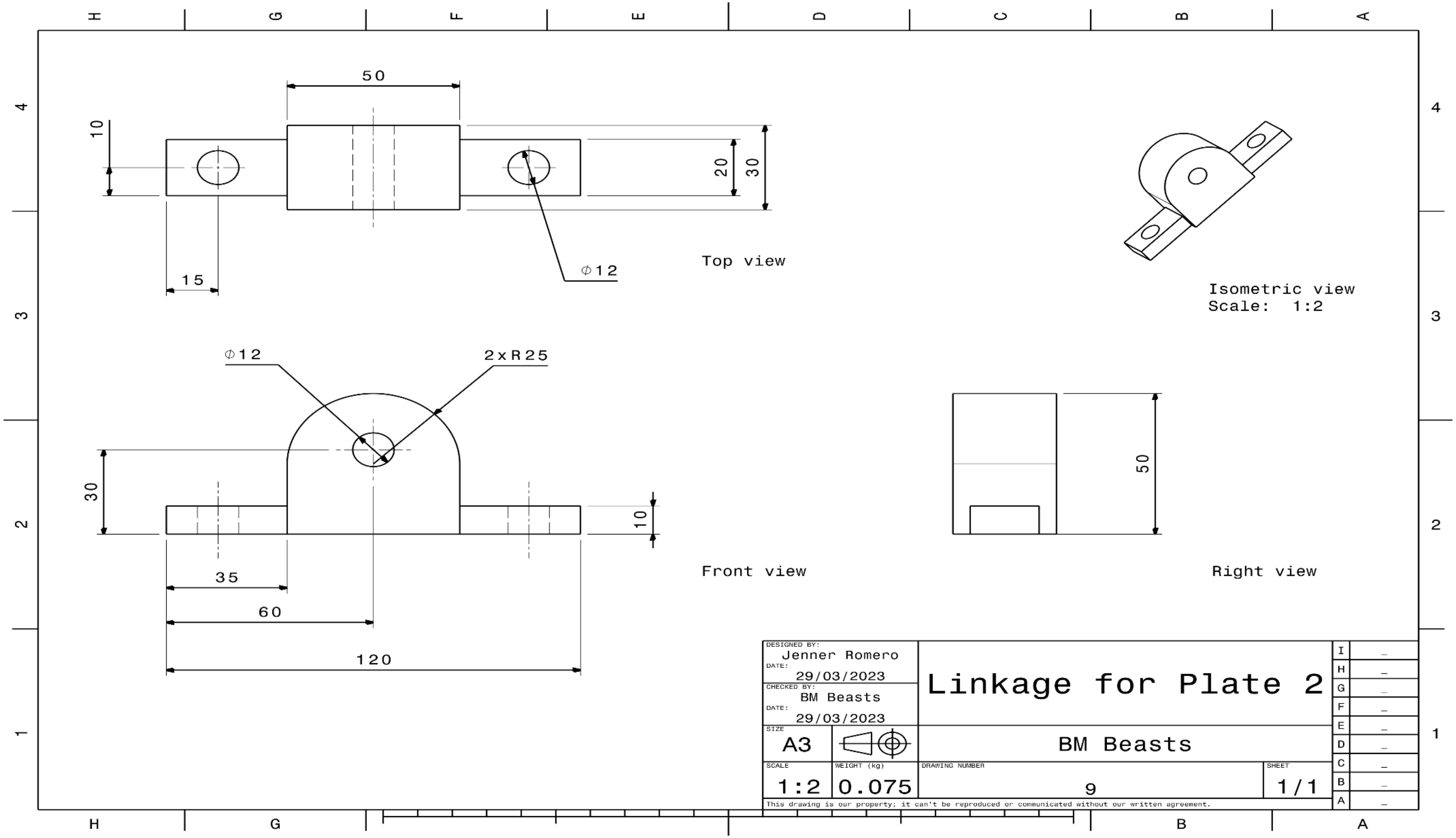
DESIGNED BY: Jenner Romero DATE: 29/03/2023	Conector with Plate 2	
CHECKED BY: BM Beasts DATE: 29/03/2023		
SIZE A3	BM Beasts	
SCALE 1:1 / WEIGHT (kg) 0.069	DRAWING NUMBER 6	SHEET 1/1

This drawing is our property; it can't be reproduced or communicated without our written agreement.


Top view
25
Isometric view
Scale: 1:3
4xΦ12
Φ50
40
15
105
200
400
80
Front view
Right view
DESIGNED BY:
Jenner Romero
DATE:
29/03/2023
CHECKED BY:
BM Beasts
DATE:
29/03/2023
Plate for Linkage
SIZE
A3
BM Beasts
SCALE
1:3
WEIGHT (kg)
0.74
DRAWING NUMBER
7
SHEET
1/1
This drawing is our property; it can't be reproduced or communicated without our written agreement.



50
10
20
30
15
Ø12
Top view
Isometric view
Scale: 1:2
Ø12
2xR25
30
10
35
60
120
Front view
50
Right view
DESIGNED BY:
Jenner Romero
DATE:
29/03/2023
CHECKED BY:
BM Beasts
DATE:
29/03/2023
Linkage for Plate 1
SIZE
A3
BM Beasts
SCALE
1:2
WEIGHT (kg)
0.075
DRAWING NUMBER
8
SHEET
1/1
This drawing is our property; it can't be reproduced or communicated without our written agreement.


50
10
20
30
15
Ø12
Top view
Isometric view
Scale: 1:2
Ø12
2xR25
30
10
50
35
60
120
Front view
Right view
DESIGNED BY:
Jenner Romero
DATE:
29/03/2023
CHECKED BY:
BM Beasts
DATE:
29/03/2023
SIZE
A3
Linkage for Plate 2
BM Beasts
SCALE
1:2
WEIGHT (kg)
0.075
DRAWING NUMBER
9
SHEET
1/1
This drawing is our property; it can't be reproduced or communicated without our written agreement.