MCGILL UNIVERSITY DEPARTMENT OF MECHANICAL ENGINEERING

MECH 292 – DESIGN 1: CONCEPTUAL DESIGN

FALL 2021

FLOOD EVACUATION VEHICLE

GROUP 2

MICHAEL BITZ - 260973800

YILAN LU - 260884151

HASHIR MAQSOOD – 260842060

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1. Introduction

1.1 Problem Statement

Due to climate change, the unpredictability of storms and resulting floods is increasing. This not only affects coastal towns but also cities further inland by means of heavy rain and hurricanes. This often leaves people stranded with no food, supplies or other essential resources. While areas that encounter this issue more frequently may have some sort of a plan to mitigate negative effects and help evacuate people, places inland that fall under the onset of sudden storms, such as the one in Houston in 2021, are left helpless. As a result, a systematic evacuation solution needs to be designed to adapt to the changing climate and varying extremities of floods, to evacuate people safely on a large-scale basis.

1.2 Relevant Statistics [1]

- In the US, death tolls related to floods have increased in recent decades to more than 100 people a year
- Drowning accounts for 75% of deaths in flood disasters
- Flood disasters are becoming more frequent, and this trend is expected to continue
- Drowning risks increase with floods particularly in low- and middle-income countries where people live in flood prone areas and the ability to warn, evacuate, or protect communities from floods is weak or only just developing
- Deaths also result from physical trauma, heart attacks, electrocution, carbon monoxide poisoning, or fire associated with flooding

Floods can also have medium-and long-term health impacts, including:

- Water and vector-borne diseases, such as cholera, typhoid, or malaria
- Injuries, such as lacerations or punctures from evacuations and disaster cleanup
- Chemical hazards
- Mental health effects associated with emergency situations and stress
- Disrupted health systems, facilities, and services, leaving communities without access to health care
- Damaged basic infrastructure, such as food and water supplies, and safe shelter

1.3 Required Functions, Objectives, and Evaluation Criteria

The design task then consists of optimizing three main objectives. This is accomplished by:

1. Making the solution as accessible as possible. In the ideal case, it is accessible to the common household.
2. Making the solution as safe as it can be for its users, as well as any other entities it interacts with throughout its lifecycle.
3. Making the solution as effective as possible in the evacuation of users.

These core objectives are then broken down into specific sub-objectives and metrics that can be used as reference design evaluation criteria throughout the later conceptual development stages. This breakdown is organized using an objectives tree [see Appendix A].

To get a better idea of which objectives are most important to us as a group, pairwise comparison charts were used at the second node level of the objectives tree, with each member contributing to the comparison and then summing the scores to get a general, however subjective, ranking of objectives within each node [see Appendix B].

The quality function deployment process was used to produce results the house of quality, which gives insight on critical functions and target values to be satisfied by our design. [see Appendix C].

Based on this, the function means tree [see Appendix D] was developed and the associated means were used to plan and develop our concepts. Functions and means were also tabulated into a morph chart to give a better idea of the available design space [see Appendix E].

According to the functional analyses, four critical functions required for the design concepts are highlighted below:

1. Move in flood conditions
2. Employ affordable materials and parts
3. Provide power
4. Enable rescue of users

2. Design Concepts

2.1 Amphibious Vehicle

2.1.1 Pre-Design Review Concept

As illustrated in Figure 1, the first of our concepts was based on the utilization of the road vehicle to navigate floods. The design consists of a transformation to a road vehicle that would allow it to travel through flood waters as well as on land safely and efficiently. The relatively reliable and long-lasting power supply of the vehicle itself is also leveraged, which is desirable in evacuation.

Figure 1: Initial Vehicle Design

The system employs two main parts to allow amphibious navigation: propellers that could be fixed to the car tires to propel it in water, as well as a tubular structure to increase the floatability of the car to remain at exactly half a tire's height above the water level. Schematics for the two main systems are shown in Figure 2.

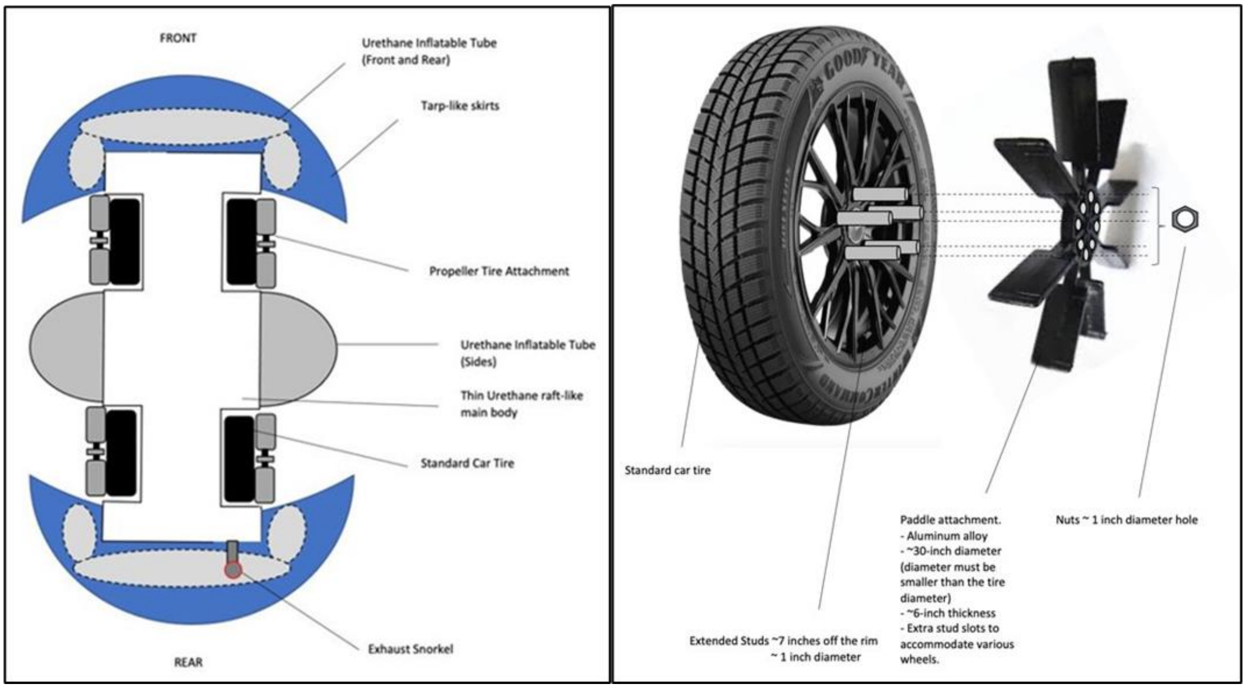


Figure 2: Preliminary Design Schematics

For the tubular floatation system, some of the preliminary design features include:

1. Front and rear waterproof skirts to prevent water being splashed up and interfere with critical component inside the car.
2. Front, rear, and side urethane inflatable tubes connected to a thin raft-like main body underneath the chassis, that altogether act to provide additional buoyancy to support the car at the desired level.
3. An exhaust snorkel to address the issue of a submerged exhaust pipe, which could cause catastrophic failure.

The propeller attachment system is designed to be compatible with standard-size car tires, with the paddle being around 30-inch in diameter so the tire steering motion would not be obstructed by the installed paddle. Extended studs of around 1-inch in diameter will be installed on the tire rim and stud slots on the paddle will allow the mounting of paddle to the tire and uniform rotation with the car tires. Compatible nuts on the other side will be used to secure the attachment. Extra stud slots on the paddle are designed to accommodate various tire models.

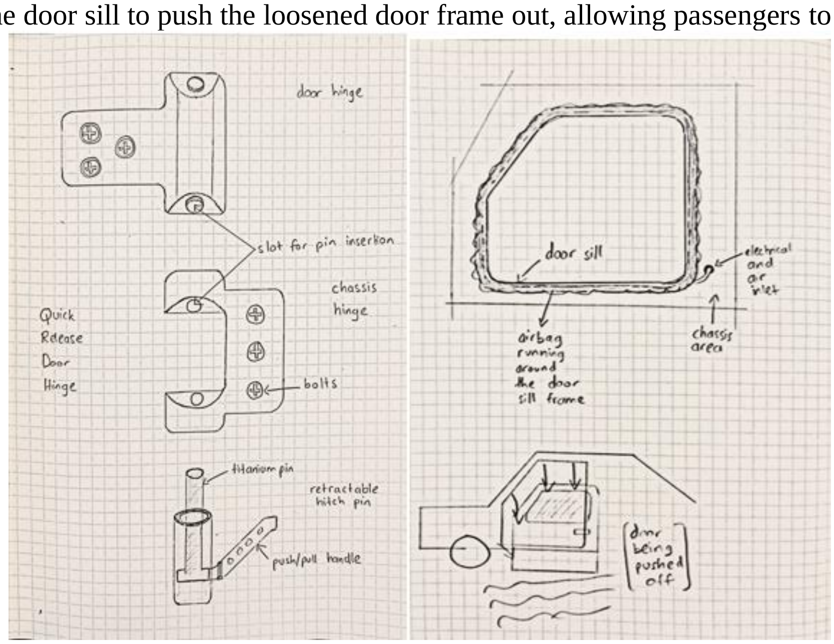
It is possible that the tubes on the side of the vehicle obstruct the vehicles motion in shallow waters or on land. To allow a quick transition from navigation in water to on land again once the side tubes are inflated, a window lift mechanism is designed to raise the side tubes above ground, as shown in Figure 3. The window lift mechanism transfers the weight of each side tube through a cable that is securely attached to the front window of the car. When the window is lowered, the resulting force raises the side tube up away from the ground increasing the clearance, allowing the vehicle to proceed without any need for users to exit the vehicle and adjust the devices manually.

Figure 3: Preliminary Window Lift Design

2.1.2 Post Design Review Modification

During the design review process, we were made aware that emergency exit measures associated with navigation in water need to be addressed, as the water pressure has the potential to block car doors from opening if the flotation system fails and the car body is submerged. This was addressed by designing an emergency exit system for vehicle passengers to escape the car quickly in such situations.

Specifically, a quick-release door hinge and air bag system was implemented as shown in Figure 4. The preliminary idea was for the door hinge to be loosened by a lever handle, allowing an inflatable airbag installed inside the door sill to push the loosened door frame out, allowing passengers to escape.



a) b)

Figure 4: a) Quick-release door hinge schematic, b) Airbag system for emergency exit

2.2 Flood Adapted Life Raft

2.2.1 Pre-Design Review Concept

Our second design concept is an inflatable life raft adapted specifically to flood evacuation situations. This concept is developed in aim to protect users in floods while enabling some degree of navigation and greatly improving the possibility of rescue. An illustration of the preliminary design concept is shown in Figure 5.

The adapted evacuation life raft combines common features of rescue life rafts with design features specifically designed for flood situations. The life raft consists of two inflation chambers that could be filled within seconds as most life rafts can using a 1-kg CO_2 cylinder [3]. The inflated volume would be around 1.3 cubic meters to achieve dimensions of 1.8 x 1.8 m and accommodate 4 people. The rigidly inflated columns that support the main shelter space of the raft can be instantly inflated by puncturing chemical mixture bags inside the structure and directly reduce inflation time [4].

Common rescue raft features are in place to ensure adequate safety. Water ballast pockets are attached to the bottom of the raft for balance and stability in strong currents. Handles are installed on the sides to support people in the raft and for transportation the raft in shallow water. Light reflecting strips are placed on the raft to improve noticeability for rescue purposes.

A solar energy driven emergency power supply system is designed for the life raft to provide short-term power capacity for communication, location, and rescue notice, all essential features for efficient evacuation. Solar energy is collected using a solar panel installed underneath the transparent waterproof top cover of the tent and stored inside a small-scale solar cell. The energy is used to power a signal light for rescue and other integrated communication devices. To protect the electrical components from water and to shield users from possibly stormy weather, the tent cover will be made from waterproof breathable fabrics. Figure 6 shows the recommended storage method for the raft. The solar panel is kept uncovered and should be exposed to sunlight for energy pre-storage in regular intervals. The rest of the raft is covered with light-reflecting and insulative wraps to extend life expectancy.

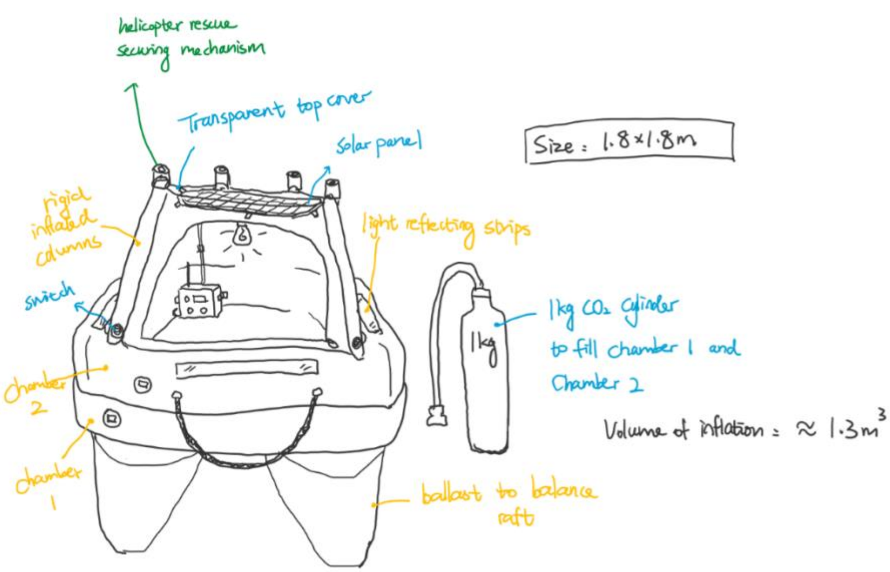


Figure 5: Schematic of flood adapted instant inflatable life raft

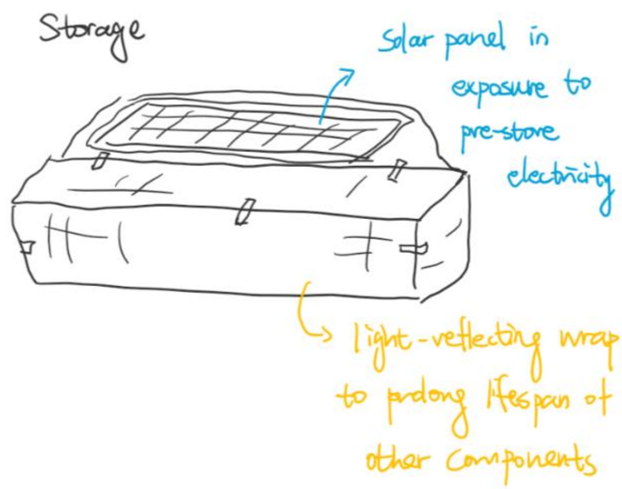


Figure 6: Recommended storage method illustration

From our House of Quality analysis, helicopter rescue is identified as one of the most employed methods for flood rescue. We have adapted our less-developed helicopter pick-up concept to be compatible with the life raft by designing a magnetic locking mechanism to facilitate aerial rescue of these life rafts as illustrated in Figure 7.

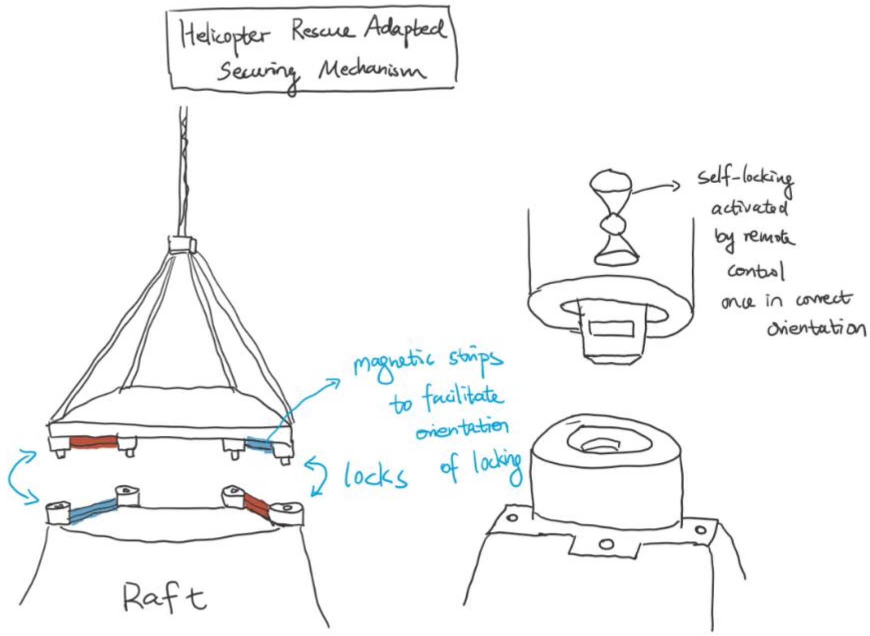


Figure 7: Compatible helicopter rescue securing mechanism on the top cover of the life raft

This mechanism employs four identical self-locking components mounted on the top of the life raft to be secured with a compatible helicopter pick-up plate lowered by a reliable cable. The turning lock could be activated by the helicopter rescue operator through remote control once the pick-up plate is aligned correctly with the raft. The orientation and alignment in unstable flooding situation is addressed using magnetic strips with opposite polarities as shown in Figure 7.

2.2.2 Post Design Review Modification

A major concern raised during the design review process is the inability of the floating raft to control its navigation direction and speed in flood, which will be a safety concern given a rush flood velocity and the possibility of contact with obstacles. As such, we modified our design to improve steering and speed control by adding on a blinder mechanism underneath the raft, as shown in Figure 8. Safety buckles were also added to the raft side enabling connection of the raft with other rafts to prevent being carried away and to build temporary shelter with other users.

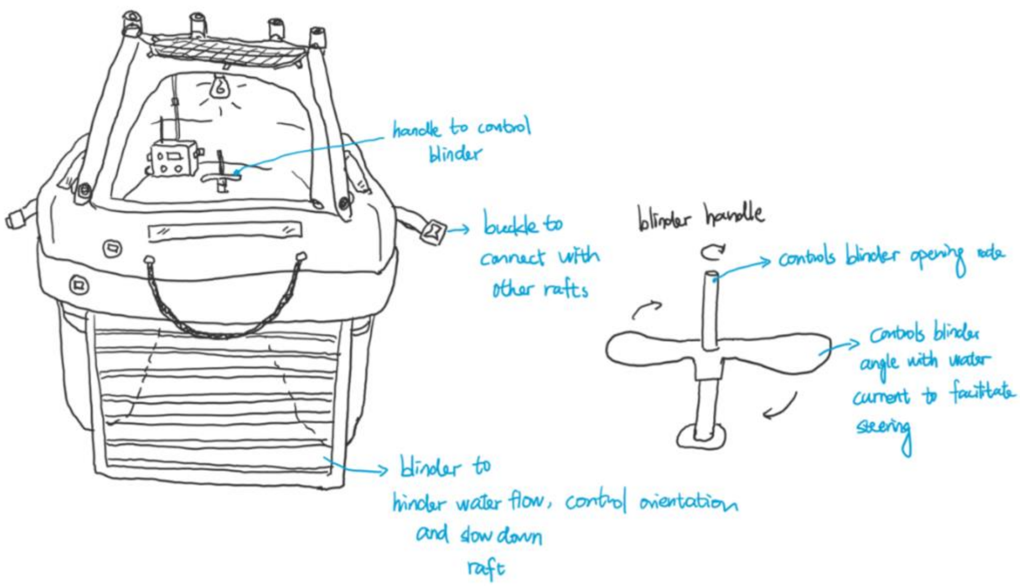


Figure 8: Modified concept with blinder mechanism and safety buckle

The blinder mechanism includes an adjustable blinder installed underneath the center of gravity of the raft (to prevent tipping moment) and a double rotatable handle inside the raft cavity. The blind opening rate can be controlled by the top handle to lower the speed of the raft in rush currents. When the blinder is fully closed, water flow is hindered underneath the raft, which provides resistance force to slow down the raft. Water ballasts help balancing the raft in this situation. The impact angle of the blinder with incoming water current could also be controlled using the horizontal handle underneath the top handle. The angle change facilitates steering of the raft by creating rotation when the water flow direction is changed underneath the raft.

This concept will have a limited sustainability potential due to its non-reusable characteristic. However, the solar panel and solar cell within the system can be recycled into useful products after the life span of the raft. Inherent flood floating risks will be associated with this design concept, and caution should be taken for waterproof design as the concept involves electrical components.

2.3 Electric Shock Proof Suit

Our third concept was generated later in the design review process due to a recognition of the need to provide an individual user-based evacuation solution that is more accessible and flexible. From feedback received during the design review, the concern of whether the operational instruction of the above two concepts would be too complex to prevent implementation on a large-scale basis was raised. Following this, the electric shock proof evacuation suit concept, shown in Figure 9, is designed to aim for maximized affordability and accessibility for individual users. This concept helps the user navigate through floods by eliminating hazards and aiding mobility. Almost no apparatus operation is required to use this suit.

One of the most critical hazards while walking through a flood would be exposure to loose wires that result in the surrounding water being capable of electrocuting people. This design is made with electric shock proof foam and rubber lining with nylon cover, which are all affordable materials to offer the solution to the general public. The chosen material also provides good heat insulation, which is desirable in flood evacuations as the temperature of water can get low. Four carbon dioxide auto-inflatable pockets are positioned in the front and back chest of the suit to increase floatability and prevent the user from drowning. When the plug is pulled, the pockets self-inflate using the same gas release technology as outlined in Concept 2. Impact absorbing foam pads are stitched inside vulnerable areas of the body as shown to protect the user from flood current and obstacle impact.

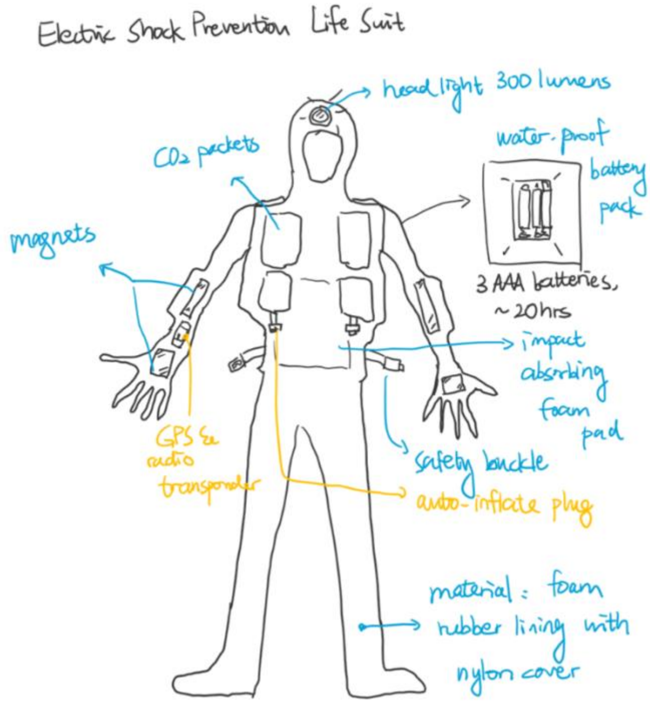


Figure 9: Schematic of electric shock proof suit

Magnets are installed in palm and inner arm locations to assist user in gripping onto metal structures, which are commonly found in a flooded urban area, to secure themselves against the current. Safety buckles are also added around the waist of the suit, which allows an individual user to secure themself to connect to other users in the flood, making navigation much safer. This feature is inspired by the current flooding situation where people usually navigate through narrow flood canals in groups holding on to each other. The gripping and attachment features on this suit can assist with evacuation for the above situation, effectively preventing people from being carried away by strong currents. For the purpose of facilitating connection with other users, the polarity of magnets on the suit is further modified, as shown in Figure 10. An opposite configuration will be available, and users can have the choice between the two.

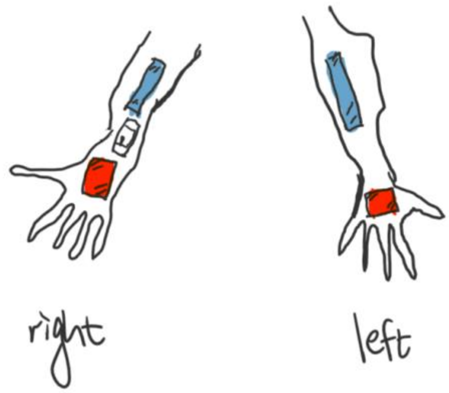


Figure 10: Magnet polarity design

The suit itself can also support a short-term communication and GPS system using a waterproof battery pack with 3 AAA batteries that could last approximately 20 h. The battery pack also powers a 50-lumen headlight to provide guidance when evacuating at night and to signal for rescue [5].

Other than the one-time inflatable carbon dioxide pockets, this concept can be reused for a limited number of times with assured quality. Individual components can also be easily recycled or reused after lifespan limit, including magnets, head light, and waterproof battery pack. The concept protects users from flood impact and water electric shock hazards, improving the safety of users when navigating through flood. Caution should also be taken in designing the circuitry of the communication device, as waterproofing is important in flood.

3. Selection Process

After the modifications to our concepts brought on by the design review process as outlined above, the concept selection process began while keeping design feedback in mind throughout.

When making decisions such as concept selection, it is of utmost importance to practice vigilance [2]. To accomplish this, the above-mentioned concepts were compared using a Pugh Matrix [See Appendix E], which uses various weighted criteria (applicable to all concepts) related to wants and needs to get a more objective ranking of the concepts. This is done by comparing solutions for each criterion relative to a reference concept. Comparisons were heavily based on external reviews from our peers to maintain as much objectivity as possible. It is important to note that Pugh Matrices maintain some subjectivity by nature of having to assign weights to different criteria and compare concepts relative to these criteria.

Nonetheless it is a very applicable means to make an informed decision. As the resulting Pugh Matrix suggests that the amphibious vehicle transformation (Datum) is the most applicable solution by a substantial margin, the concept was unanimously agreed upon by all members of the group and selected as the final concept.

4. Final Concept

4.1 Overview

The best way we measured to balance our critical functions was to leverage an existing yet vulnerable resource in flood situations, the road vehicle. If we could make a road vehicle mobile on water and sufficiently safe, we would not only have a very affordable solution accessible to just about anyone with a car, but also preserve the value of these expensive vehicles, usually rendered useless in a severe flood. The manipulation of an existing vehicle would allow us to leverage all the existing components essential to mobilization, making for a much more accessible and scalable solution. A to-scale CAD model assembly in Figure 11 shows our final design of amphibious adaptation to a typical sedan car, with waterline position indicated.

This solution allows the car to move efficiently using the propeller system. It keeps the vehicle and its users safe above water using a reliable inflatable tube fitted directly to the vehicle. It employs common materials and parts, as well as employs an existing power source keeping the cost low and accessibility very high and overall enables the rescue of users by providing a means to navigate safely and efficiently through flood conditions.

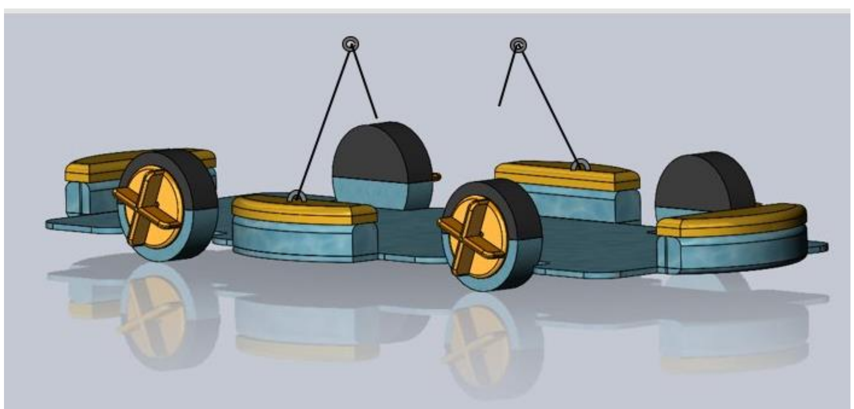


Figure 11: Rendering of the Amphibious Vehicle Adaptation

4.2 Proof of Concept

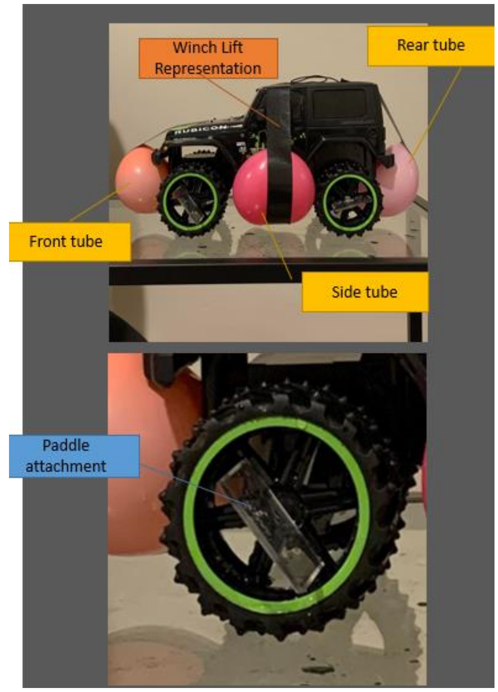


Figure 12: Prototype Cutting through Water

Figure 13: Prototype Design

To demonstrate the actual working of our concept in the real world, we were not able to replicate the full-scale application due to limited time and resources. As an alternative, we developed a small-scale prototype with the same functionality. Its primary features being mobility on land and water.

The specific details of how each component works is highlighted in the following sections. But essentially, the rubber tubes as shown in Figure 12 served as the flotation system, and the acrylic paddle attachment shown in Figure 13 served as the wheel propellers. With only these two additions to a remote-controlled car, powered by an electric motor, the prototype was able to drive on land as well as navigate in water.

For the simulation of flood water, we filled a bathtub with water. Once the car was placed inside, the flotation system performed better than expected and the water reached the ideal halfway point of submergence of the wheels. Next, we tested the forward, reverse, and turning motions of the car which, it was able to do adequately while cutting through the turbulence produced.

One concern that was noticed during the design phase was the interference of the tubes on the ground once the water receded or land approached. To tackle this, we attached cables holding the tubes to the roof of the car – such that it lifted them high enough to provide driving clearance. In the full-scale model, this feature would be replicated by a winch lifting system.

4.2.1 Flotation Device

Figure 14 shows the free body diagram of a car in water with a net forward acceleration.

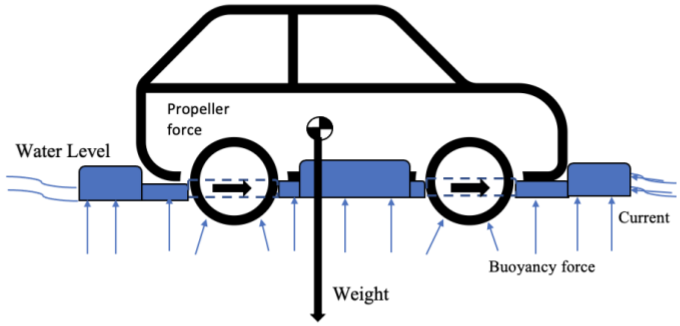


Figure 14: Buoyancy Free Body Diagram

As shown in the free body diagram above, for the car to float, the buoyancy force produced by the displaced water volume should be equal to the weight of the car. To ensure that the concept would float adequately, Equation 1 is used to get an approximate required buoyancy force [6].

$$F_b = -\rho \times g \times V \quad (1)$$

Equation 1 demonstrates the Archimedes principle where F_b is the buoyancy force, ρ is the fluid density – 997 kg/m^3 for water, g is the acceleration due to gravity, and V is the submerged volume of the object. In the initial stages of our design, the general case of a compact sedan was taken which has a total weight of 1680 kg. To support or float this, an equal in magnitude buoyancy force must be produced. Therefore, by Equation 1, the submerged volume of the flotation tubes must be 1.69 m^3.

To determine which material would best match the requirement of the task, a comparison chart between common flotation raft materials was created between their advantages and disadvantages.

Table 1: Tubing Material Comparison [7, 8, 28]

	Advantages	Disadvantages
Polyurethane	- Difficult to weld and glue	- Lower melting point
Hypalon	- More chemically resistive - Very tough	- More expensive
PVC	- Best UV resistance - Cheapest	- Brittle in cold temperatures

Based on these findings, it was decided that the tubes be composed of 0.9mm thick Hypalon as it has superior thermal resistance, useful under the hot car underbody, and tear resistance. The material can also elongate 500% up till failure with durability of 7+ years. For inflation, Nitrogen was chosen as the preferred gas as it is stable in varying temperatures and disperses evenly during inflation. As a result, the inflation time expected is 10 seconds at the maximum air flow rate which is supplied by the canister stored onboard the car containing 0.8 kg of Nitrogen.

A simple attachment system of the tube to the bottom car utilizes four carabiners latched at each end of the car chassis, as shown in Figure 15. This latch mechanism allows for secure grappling while keeping the tubes modular as they allow quick deployment of the tubes. A schematic showing the specific attachment locations is shown below.

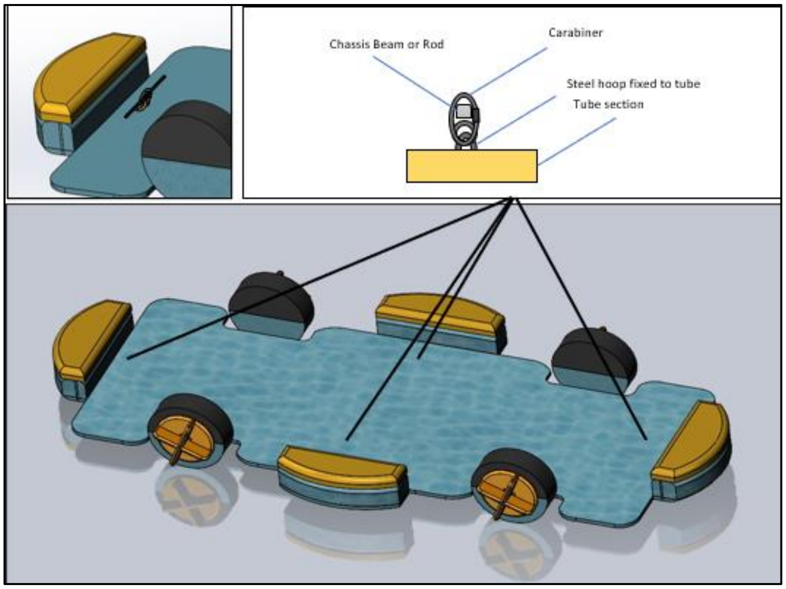


Figure 15: Tube Attachment System

4.2.2 Wheel Propellers

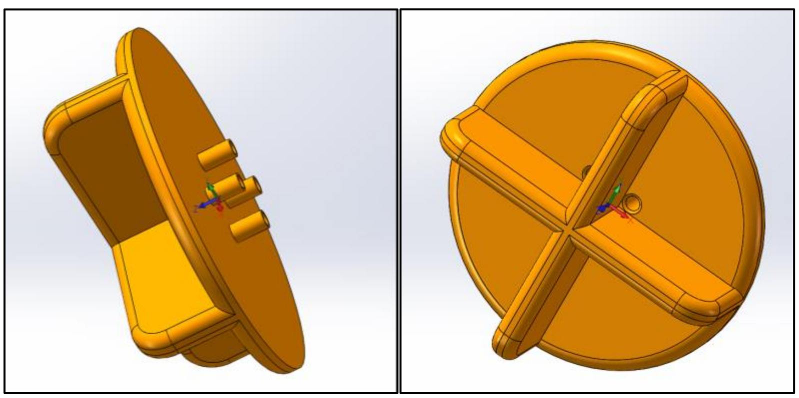


Figure 16: Wheel Paddle Attachment Rendering

To provide controlled propulsion in water, a means to leverage the rotary motion of the wheels was required. Therefore, we developed a paddle attachment for the wheels that can cut and push through flood water. The functioning of the propeller is described by the free body diagram below.

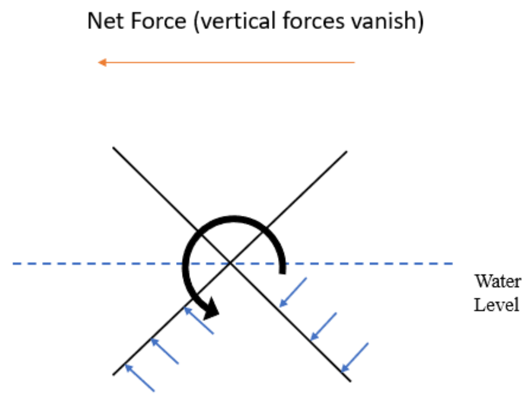


Figure 17: Wheel Paddle Free Body Diagram

As the wheels of the car turn, powered by the engine, the propellers move with the same rotational speed. Here, the portion of the paddle that is submerged in water experiences an opposing force to its motion due to the mass and current of the water. This is similar to the friction present between the tires and ground when it is moving on land. Assuming the propellers are maintained at the ideal level of exactly halfway underwater, they create a net horizontal force as indicated above the diagram.

To accurately model this system in water, there are various complex differential equations that simulate the actual force of a moving fluid against an obstruction. However, a simple baseline that we used to estimate the force of water was through Equation 2 [9].

$$Force = Area \times K \times Velocity^2 \tag{2}$$

Here, K is the drag coefficient. For a rectangular paddle, the value of K can range from 1.8 to 2.0. Using the dimensions of the paddle and the velocity based on the RPM, the force acting on a single paddle can be calculated. This can then be multiplied by the number of paddles to get the net force of approximately 233.6 lbs. For a standard sedan that has a horsepower figure of 169-hp, the torque produced is sufficient to navigate capably in standing water. It is worth noting however that this is meant to be an emergency measure to preemptively evacuate the affected area rather than through a severe and fast-moving flood.

More specifically, the propeller was designed with a disc at the base to cover the car rims, which avoids any turbulence and other unexpected behavior by preventing flow of water across the base of the car horizontally. The base disc attaches to the rims using the stud channels and is bolted on by the regular lug nuts. In terms of composition, the entire component will be made of 6061 Aluminum due to its high yield strength of 276 MPa while maintaining a relatively low mass at a reasonable cost [16, 17].

4.2.3 Winch Lifting System

The entire concept of this solution depends on the ability to quickly change terrain from water to land. So, a concern that arises here is the interference of the flotation devices around the car with the road. To solve this, a winch and pulley system will be installed between the roof racks that pulls the tubes up using steel cables when approaching land to provide enough driving clearance. With the mass of the flotation device supported being 1.67 kg, the use of a steel cables with a diameter of 2.38 mm that provides a working load limit of 90 kg is more than sufficient. The workload limit of our chosen double winch – Jeamar Winches GWF 550 has a manual force required of 35 N, which is achievable by an average person [10].

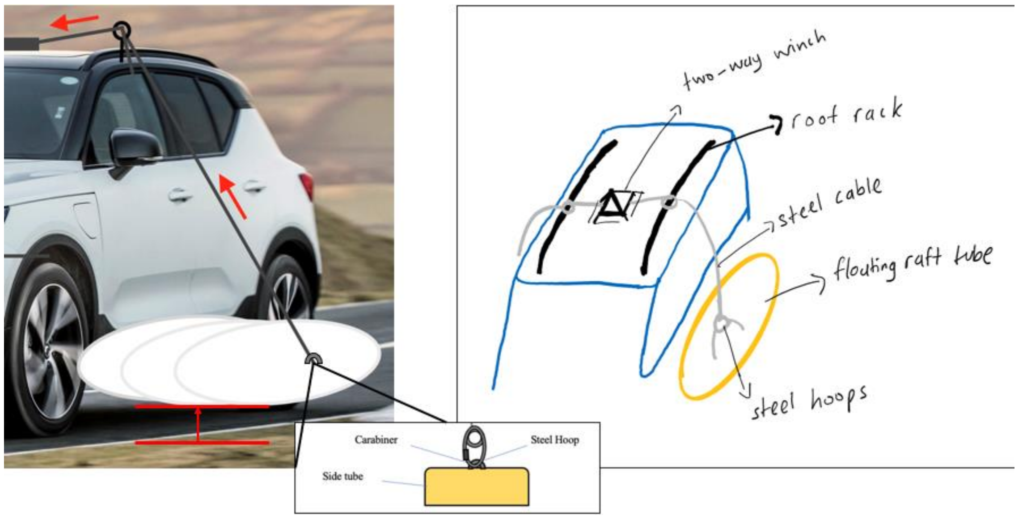


Figure 18: Winch Lift Schematic

Additionally, Figure 19 shows the two different positions of the tubes on the scaled down proof of concept:

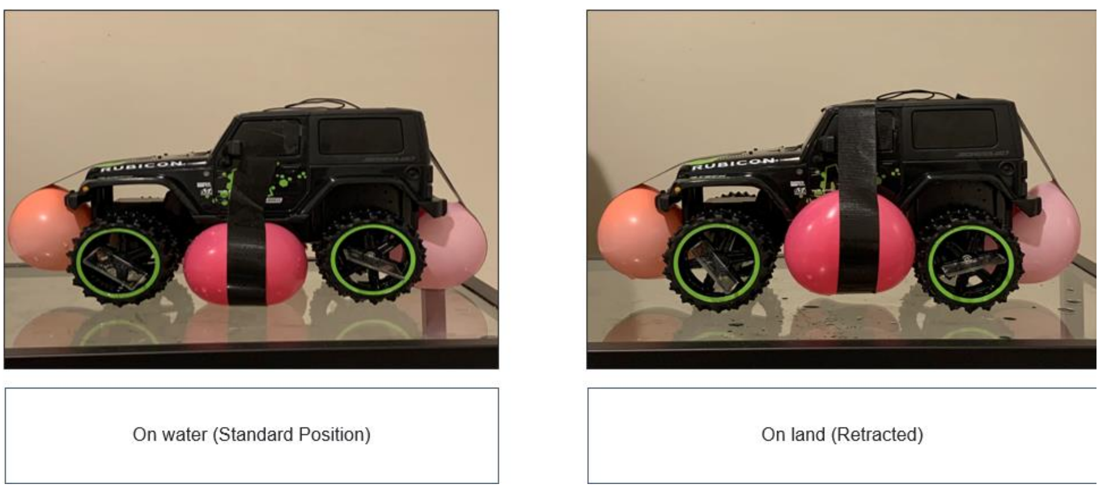


Figure 19: Different Positions of the Flotation Tubes

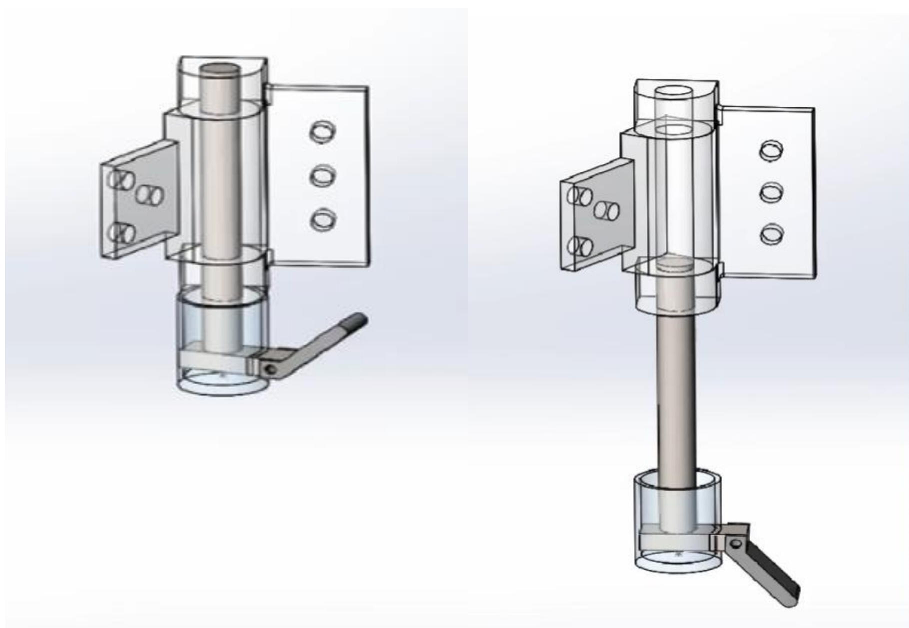
4.2.5 Quick-Release Door Hinge

While going through the obstacles that arise in the case of floods, one of the most important ones was getting trapped and, in this case, – in a car. So, during our design review, we developed a quick-release door system that could be used in an emergency to escape the vehicle. While it may not have been entirely consistent with the preceding concepts in our design problem, this solution integrates well with the amphibious vehicle. Essentially, the goal is to be able have an open and safe passage to escape which might not be possible if the door is jammed due to the water pressure or other debris such as tree branches.

Typically, vehicle door hinges are designed with two pieces – 1 on the chassis and 1 on the door – and either one of them contains the mating hitch pin that holds on the door. The quick release system makes this design modular so that the hitch pin is an individual component that normally slides into the other two parts to hold on the door. In the case of an emergency, the pin can be retracted so nothing is holding on the door.

Next, there is a tube airbag going around the door sill on the chassis frame which when activated will inflate create a controlled impulse force to push off the door. It also has the added benefit of acting as a seal against water while it is intact.

The hitch-pin insert mechanism and the hinge assembly will be made with steel, which has a high shear strength (0.75 x UTS) that is desirable for locking and holding the hinges in place against shearing and torsion loads [11, 12]. The designed hinge assembly has an insert diameter of 35 mm and will need 6 x 20 mm Dia. Bolts to secure. The dimensions are to scale with reference to a typical car door hinge specification [13].

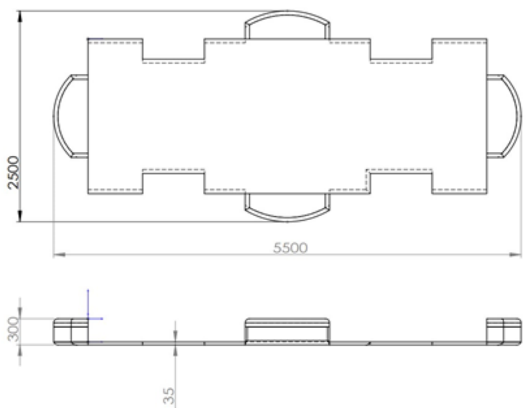


a) b)

Figure 20: Quick Release Door Hinge To-scale Model a) Secured position b) Release position

4.2.5 Technical Schematics [14, 15, 18, 19]

The drawings in this section have all units in millimeters.

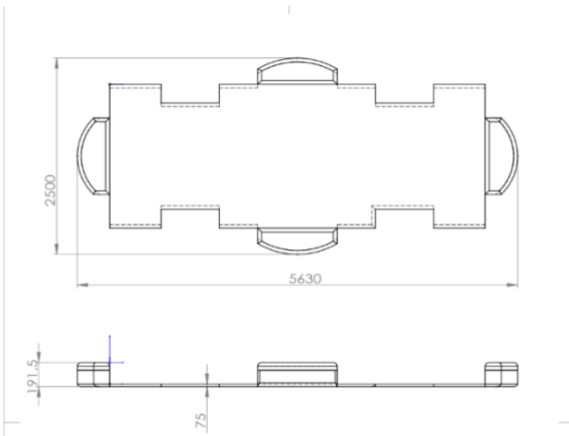


Car Type
Compact Sedan
5-Person Capacity
1400 kg

Dimensions
4.6 m x 1.8 m
Ground Clearance: 135 mm
Tire Diameter: 635 x 195 mm

Paddle Design
440 mm diameter
4 Paddles

Figure 21: Tube Design (Compact Sedan)

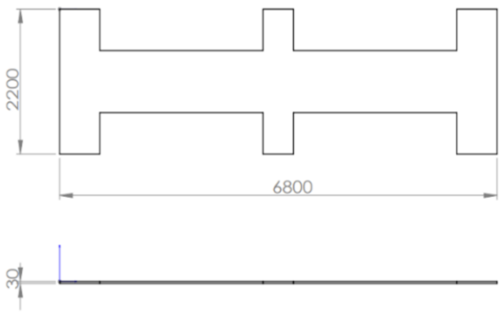


Car Type
SUV
5-Person Capacity
1700 kg

Dimensions
4.85 m x 1.825 m
Ground Clearance: 225 mm
Tire Diameter: 663 x 235 mm

Paddle Design
470 mm diameter
5 Paddle

Figure 22: Tube Design (SUV)



Car Type
Mini Van
7-Person Capacity
2600 kg

Dimensions
6.7 m x 2.1 m
Ground Clearance: 14 mm
Tire Diameter: 668 x 215 mm

Paddle Design
470 mm diameter
5 Paddles

Figure 23: Tube Design (Mini Van)

Note in the case of the minivan the clearance under the car allows for enough tubular volume to float the vehicle without substantially extruding the tubes around the vehicle as seen in the other models.

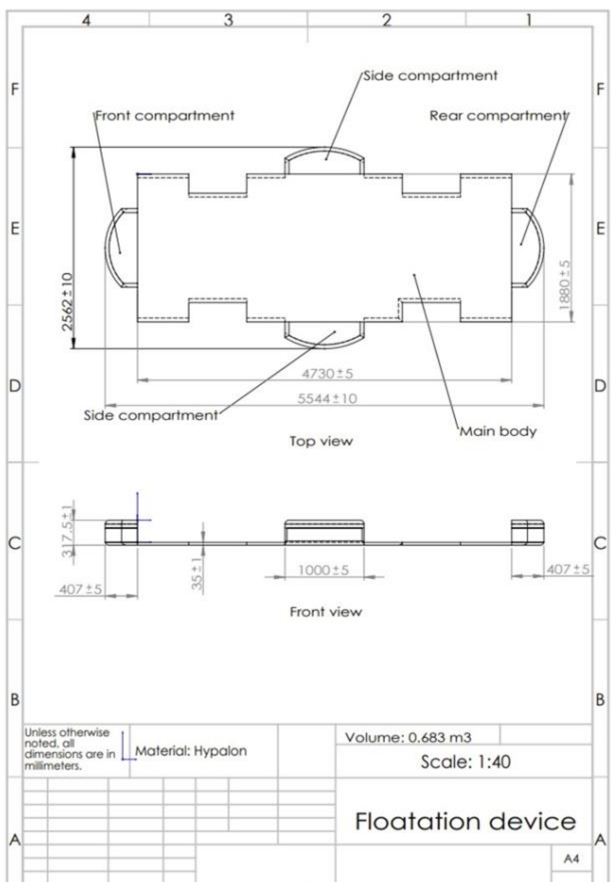


Figure 24: Flotation Device Technical Drawing

4.3 Secondary and Undesired Functions

(i) Submerged exhaust pipe

Since most vehicles on the road are currently gas powered, they need a clear path of air circulation for combustion in the engine. If the car is submerged above its wheels, the water will flow into the intake and exhaust leading to compression issues in the engine. As there is no further place for the water to go, the piston rods will eventually buckle and fail, defeating the entire concept of emergency evacuation.

To solve this issue, we are combining our concept with the existing solution of a 'vehicle snorkel'. It is commonly used by people while off-roading. Essentially, it reroutes the air channel of the intake and exhaust along the A pillar of the car to an elevation where the water cannot penetrate.

(ii) Sharp corners on flotation tubes

Having straight defined edges in the flotation tubes can lead to several issues such as inconsistent inflation of gas, creation of local stress concentration regions, and risk of puncture upon external impact. As a result, the design of the tubes was modified to create rounded edges between the sides and planar faces to resolve these issues. Additionally, this will also alleviate the flow of water around the tube resulting in less drag force.

(iii) Usage of Carbon Dioxide to inflate tubes

During our research, it was found that carbon dioxide fluctuates in pressure with changes in temperature. This is not a desirable quality for inflating a support device such as flotation tubes. Additionally, carbon dioxide spread unevenly which would lead to inconsistent inflation times that can cause delays in evacuation time. Therefore, the inflation mechanism replaced carbon dioxide canisters with nitrogen canisters which is much more suitable in the environments that the vehicle would be facing.

(iv) Excessively large flotation tubes causing difficulty in navigation

Another concern that arose in terms of the design of the flotation system was its size making it difficult to navigate in relatively tight areas. Since the volume of air in the tubes required to provide the necessary buoyancy force is non-negotiable, the design was altered to maximize the size of the tubes in the back and front of the car while maintaining its balance. The rationale behind this change was that the footprint of the car in its forward direction of motion that is most used. Additionally, a secondary feature that arose from the design of the tubes, owing to the durability of the Hypalon, was additional padding around the vehicle to sustain minor shocks without causing damage to the car or its occupants.

4.4 Performance Targets

According to the House of Quality analysis, critical performance targets are identified for the design solution and will be discussed below with performance analyses of the design solution.

(i) Weight

We have set the weight target to be less than 100 kg added to the original weight of the car. This target is set considering a comparison with existing solutions and delighted/disgusted values outlined in the House of Quality. Table 2 displays the mass of individual components in the designed system for a typical sedan.

Table 2: Component mass of the amphibious flood evacuation adaptation system for a reference sedan

Component	Mass [kg]
Paddles + attachment x 4	40
Inflatable raft + attachment (after inflation)	10
Gas canister	0.8
Winch lift system	14
Exhaust snorkel	1
Adapted door hinge system x 4	24
Total Mass	89.8

The values displayed in Table 2 are estimated from the volume of individual parts and their material density. From Table 2, we conclude that the designed system satisfies the weight target and has a performance factor of 1.11, calculated using Equation 3.

$$Performance\ Factor = \frac{Target\ value}{Performance\ value} \tag{2}$$

It should be noted that this weight performance analysis used a specific reference case using a small-sized sedan for the calculation of inflatable raft weight and gas canister weight. For other vehicle sizes, these values will be subject to small changes. For SUV, a slight increase of inflation volume and gas weight (1 kg) is needed, and for the mid-van case, a decrease of the above weight is achieved. Therefore, we conclude that the sample sedan weight performance is representative of an accurate estimate weight of our designed system and that it satisfied our initial target. We can also conclude that the add-on weight of the adaptation could be neglected with regards to the typical weight of 1500 kg of vehicles and will have minimal influence on the buoyancy of the car.

(ii) Manufacturing

Since a key attribute of our device is to be maximally accessible, large-scale production and affordable price are essential, as such, simple manufacturing methods are required. According to our House of Quality, a "delighted" manufacturing process of our design solution would be similar to that of a small manual boat, and a "disgusted" manufacturing process would be more complex than that of a car. Based on this, we have set our target value for each individual manufacturing process to be completed in under 10 hours. This would be achievable using simple manufacturing processes such as machining, casting, and injection molding. Table 3 summarizes manufacturing methods and average time required for individual components of our designed system.

Table 3: Manufacturing analysis of the designed adaptation system [20, 21]

Component	Manufacturing method + estimate time	Estimate time [hours]
Paddles + attachment	CNC milling	4
Inflatable raft + attachment	Glue and adhesives rolling	3.5
Gas canister	Existing cylinder recharge	0.08
Winch system	Existing product assembly	0.17
Exhaust snorkel	Die press extrusion	0.5
Adapted door hinge	Thermal treated casting and machining	1
Tubular air bag	Machine sewn	0.3
Total Time	--	4 (if all proceed simultaneously)
Total Cost	--	$ 150

In Table 3, the estimated total cost of the manufacturing process takes into consideration variable costs including labour and machine operation using the estimated time of manufacturing. An extra fixed cost for casting and die extrusion tooling will be applied, estimated to be around $1000 for the entire production process.

Through manufacturing analysis, we conclude that the design is manufacturable using simple and cost-effective manufacturing methods. Complex manufacturing processes such as multiple axis machining or 3D printing are not required. The target of each individual process to have an average time under 10 hours is achieved comfortably. Overall, the time consumption and cost budget related to manufacturing make the designed solution suitable for mass production and application for general household uses for evacuation.

(iii) Life Cycle Cost

For maximized accessibility and affordability to a general household, the cost target of our designed product is set to be less than $ 3000. The initial cost of our product is around $ 950 as estimated in Table 4. The life cycle of a product starts with manufacturing, is followed by operation, and ends with disposal and possible recycling. The costs associated with each stage in the life of a product include initial cost, service cost, maintenance cost, operating cost, and disposal cost [22]. Table 4 summarizes these costs at each stage of the life cycle for our amphibious vehicle adaptation system.

Table 4: Life cycle cost analysis for designed system

Initial Cost	Raw material	$ 806.2
	Manufacturing & Assembly	$ 150 ($ 1000 fixed cost)
Service Cost	Packaging & Transport	$ 50
Maintenance Cost	On-demand repair	$ 1
Operating Cost	Replacement of expendables	$ 100
Disposal Cost	Disassembly	$ 15
	Treatment or recycling	$ 350
Total Cost	--	**$ 1448.8**

The initial cost consists of raw material cost and manufacturing & assembly cost. The raw material cost is estimated using individual material unit cost and the mass of each component. The manufacturing and assembly cost is converted from manufacturing and assembly time for each component, as displayed in Table 3. A fixed cost of mold tooling construction will also be added to the production process. The service cost mainly includes packaging and transport of the product to customers, and this cost is estimated to be $ 50 per product as attention needs to be placed for packaging and securing critical components such as the pressurized gas canister. The maintenance cost consists of on-demand repair requests from users. According to the degree of damage or failure, the cost will vary but will have a limit of the total initial cost of the product, which is $ 956, multiplied by the probability of on-demand maintenance request within covered period, estimated to be 0.1 %. There would be cost associated with operation, which mainly consists of replacement cost of expendable items in the system. The major replacement item per operation would be the gas canister. The disposal cost will be estimated using disassembly cost and treatment or reuse cost of disassembled parts. It is estimated that an average of 1 h will be used to disassemble the system, therefore the cost is estimated to be $ 15. The major cost for treatment and recycle of waste material is contributed by incineration of Hypalon, which is estimated to be $ 300 using the method in [23]. Other components such as metal parts will be either landfilled or recycled. The associated cost is estimated by the transportation cost to be around $ 50 per system.

Overall, the product has a lifecycle cost of $ 1448.8 per individual product. The production process also requires a $1000 fixed cost. It should be noted that the designed system has a limited ability for recycle and reuse, especially regarding the Hypalon flotation tube, which is considered toxic to the environment. The long-life span of individual product compensates a percentage of this drawback. Nonetheless, the product design comfortably meets the cost target based on the estimated values.

(iv) Sustainability and Safety

Although our design does not contribute directly to alleviating climate change or global warming, it aids greatly in managing a severe consequence of this issue. Furthermore, given its emergency use nature, it is not expected to have any substantial impact on the environment and should not raise any sustainability concerns. Furthermore, its reusability and long-life expectancy remove any concern for wasted materials. The Hypalon flotation tube usually has a life expectancy of 7-15 years [24]. Due to the intended usage of emergency evacuation, the system will not be under constant operational stress, so the life expectancy of the entire system is expected to be around at least 5 years. The operation of the system leverages existing energy, and its low mass reduces energy consumption. Limitation regarding sustainability for this design would be the difficulty to recycle the materials after the system reaches its life limit.

As for safety, it’s important to understand that no floating vehicle, especially this affordable and scalable will ever be perfectly safe. That said, given the nature of its use in emergency flood situations, the potential rewards of its use far outweigh the associated risk. Reliable materials are chosen for each component of the designed system that are proven to withstand loads incurred during operation. The emergency exit door hinge system also provides additional safety back-up in case of vehicle failure. The above features improve the overall system reliability of the design. It should be noted that potential safety concerns associated with this design include risk of puncturing the flotation tube and risk of water leaking into critical components of the vehicle, which introduce some limitations to the design. Redundant detailed designs, such as increasing the number of chambers inside the flotation tube, would improve system reliability in case of single chamber failure, with the sacrifice of increased inflation time.

5. Bill of Materials [25, 26, 27]

Table 5: Bill of Materials

No.	Part number	Item	Material	Quantity	Source	Price Estimate
1	--	Tire Propeller Attachment	6061 Aluminum	4	Manufactured	$ 100
2	--	Nitrogen gas canister	Mild steel	1	Adarsh Oxygen	$ 55
3	3A5009	Tube body	Hypalon	1	Manufactured Sanhe Bestrubber	$ 300
4	42934	Carabiner	Steel	8	Everbilt	$ 10 x 8
5	811042	3/32 in. x 50 ft. cable	Steel	1	Everbilt	$ 25
6	811168 & 43864	Attachment ring and D-ring	Steel	2 each	Everbilt	$ 5.20
7	--	Tubular airbag	Nylon	4	Manufactured	$ 70
8	--	Hitch pin retraction mechanism	304 Steel insert 6061 Aluminum hinge	4	Manufactured	$ 45
9	--	Exhaust snorkel	6061 Aluminum	1	Manufactured	$ 26
10	GWF 550	Double winch	--	1	Jeamar Winches	$ 100
Total Material Cost		**$ 806.2**				

6. Conclusion

In this project, we addressed the climate change adaptation design problem of developing flood evacuation technology to evacuate civilians safely and efficiently on a large-scale basis considering the context of unprepared sudden flood in inland cities. After defining the problem and setting out required objectives, we analyzed the required functions needed for the design to effectively mitigate the problem presented. Three concepts were developed during the concept generation process. The first is a flood evacuation amphibious adaption system for common road vehicles that allows for safe and protected navigation in water and on land for users. The second concept is an instant inflated life raft adapted with speed control and rescue compatible mechanism for flood evacuation purposes. This concept allows users to prepare the evacuation in the shortest time possible. The third concept is an electric shock proof suit that is equipped with gripping and securing mechanisms to assist navigation of individual user through flood with maximal flexibility and accessibility.

Our concept selection process is conducted with the aid of a Pugh matrix. According to the weighted criteria comparison, we decided to develop the amphibious adaptation system for road vehicle as our final selected concept for the problem of flood evacuation. A proof of mobility of this concept employing a scaled-model prototype is developed. Detailed design and calculation for individual subsystems within the design are conducted. The conceptual design process is thorough and extremely technical, going through this allowed us to develop a final concept that not only satisfies our problem statement and design challenge, but also that does so efficiently and most effectively.

Target evaluations are conducted for the final developed design. The final design successfully meets the weight, manufacturing, and cost target values. During the lifecycle, sustainability, and safety analysis, some limitations of the design are revealed. Although the system has a relatively long and reliable life expectancy, after its life span limit, the components will be difficult to recycle and reuse. Inherent safety risks associated with navigation in water are also present for the design, as flood situations are often unpredictable and could pose unexpected hazard when the system is in operation.

6.1 Lessons Learned

Many lessons were learned throughout the project timeline, most notably in the prototype development process:

- Adequate research of the problem and identification of required functions and demands from different perspectives (recognizing the stakeholders) are critical to further understanding of the design problem. This preliminary definition stage contributes to effective concept generation and the possibility to address the problem from a more comprehensive point of view.

- Analyzing targets (such as in the House of Quality) early on helps to direct the design and ensures that the concepts generated will be satisfactory for the specific problem addressed.

- Calculations of critical loads and forces to ensure the validity of the design in the prototype development process is essential, as our original concept of a window-lift system was proven inadequate to provide the required power and we modified the design to a winch system as result.

- Sustainability and disposal of the designed system are important aspects to consider, as they represent a major part of cost in the lifecycle of the product. Most specifically, material selection is crucial to the disposal stage as different materials have characteristic properties that influence long time sustainability.

- Teamwork is of utmost importance in any group design project setting. Adequate teamwork and communication were entirely responsible for the completion of the design task.

- When something is unclear, it is essential to ask for further clarification instead of guessing and proceeding. This is especially important in a design setting where a client is being served. This was understood when we proceeded with our alternative design concepts without fully comprehending the extent of development required.

A. Objectives Tree

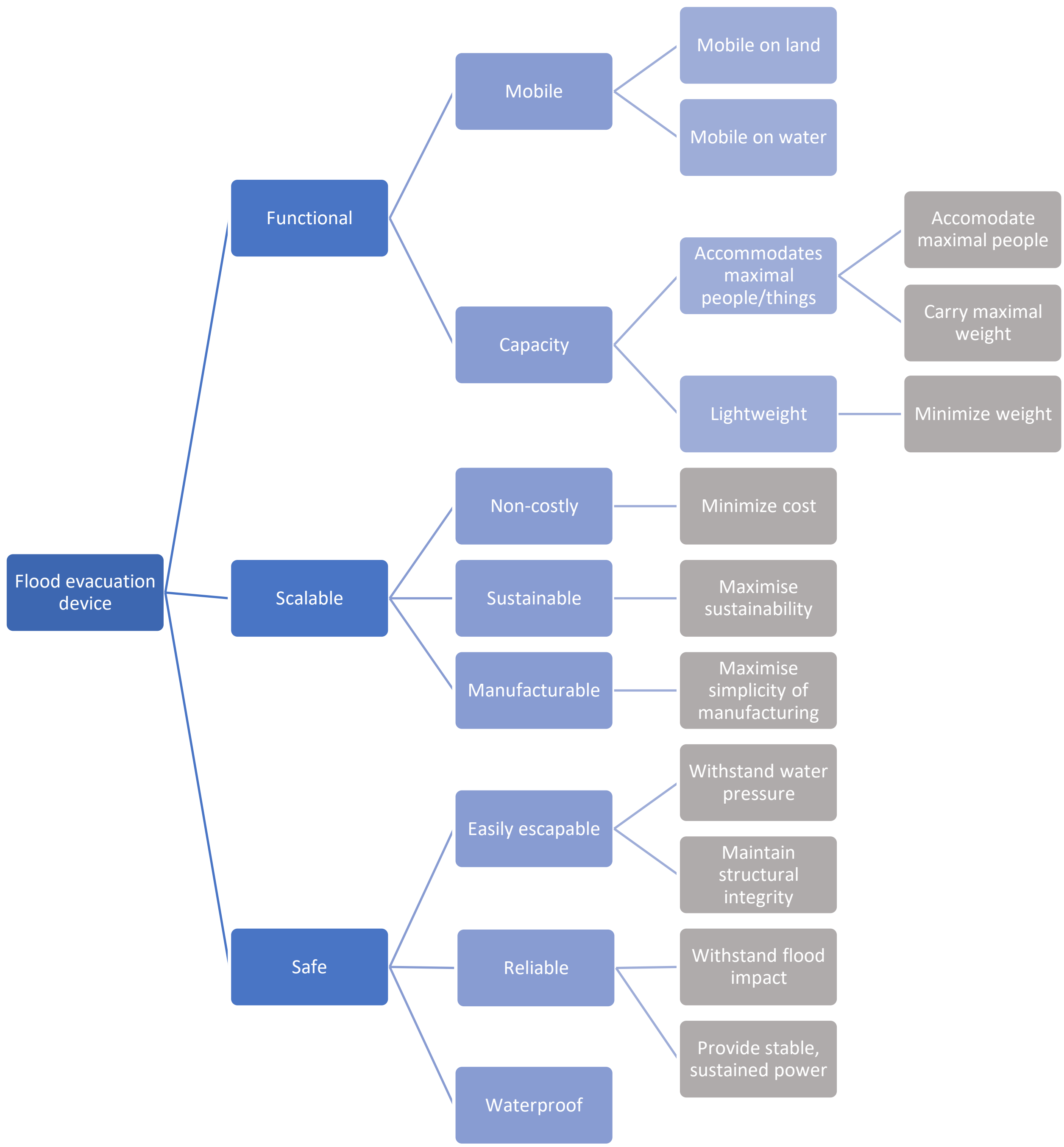


Figure A1. Objectives Tree

B. Pairwise Comparison Chart

Table B1. Pairwise Comparison Chart for Scalability Objectives for 3 Designers

Goals	Cost	Sustainability	Manufacturability	Score
Cost	--	1 + 1 + 1	1 + 1 + 1	6
Sustainability	0 + 0 + 0	--	0 + 0 + 1	1
Manufacturability	0 + 0 + 0	1 + 1 + 0	--	2

Table B2. Pairwise Comparison Chart for Safety Objectives for 3 Designers

Goals	Escapability	Reliability	Water Resistance	Score
Escapability	--	0 + 1 + 0	1 + 1 + 0	3
Reliability	1 + 0 + 1	--	0 + 0 + 1	3
Water Resistance	0 + 0 + 1	1 + 1 + 0	--	3

Table B3. Pairwise Comparison Chart for Functionality Objectives for 3 Designers

Goals	Capacity	Mobility	Score
Capacity	--	1 + 0 + 0	1
Mobility	0 + 1 + 1	--	2

C. House of Quality

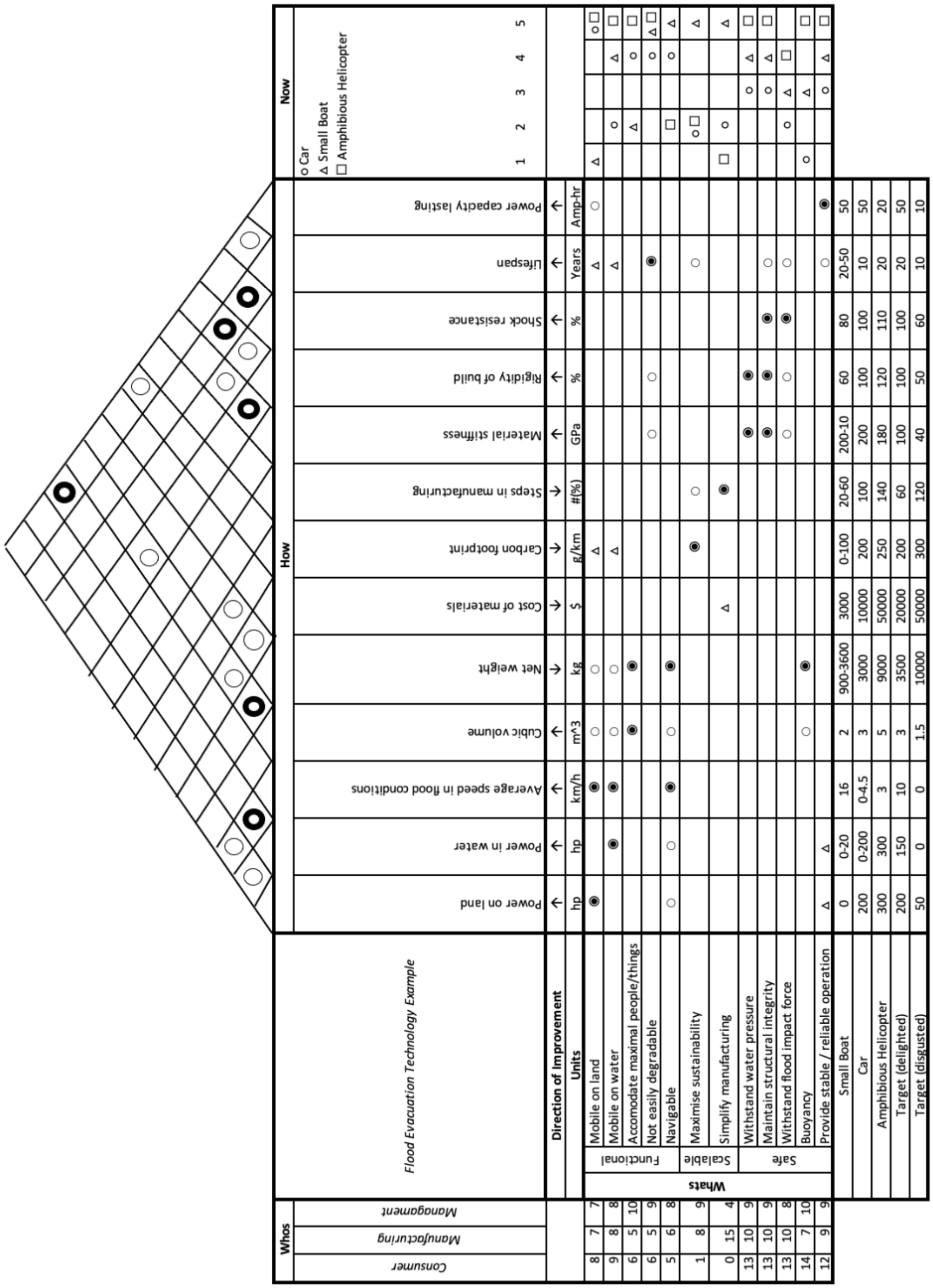


Figure C1: House of Quality

D. Function-Means Tree

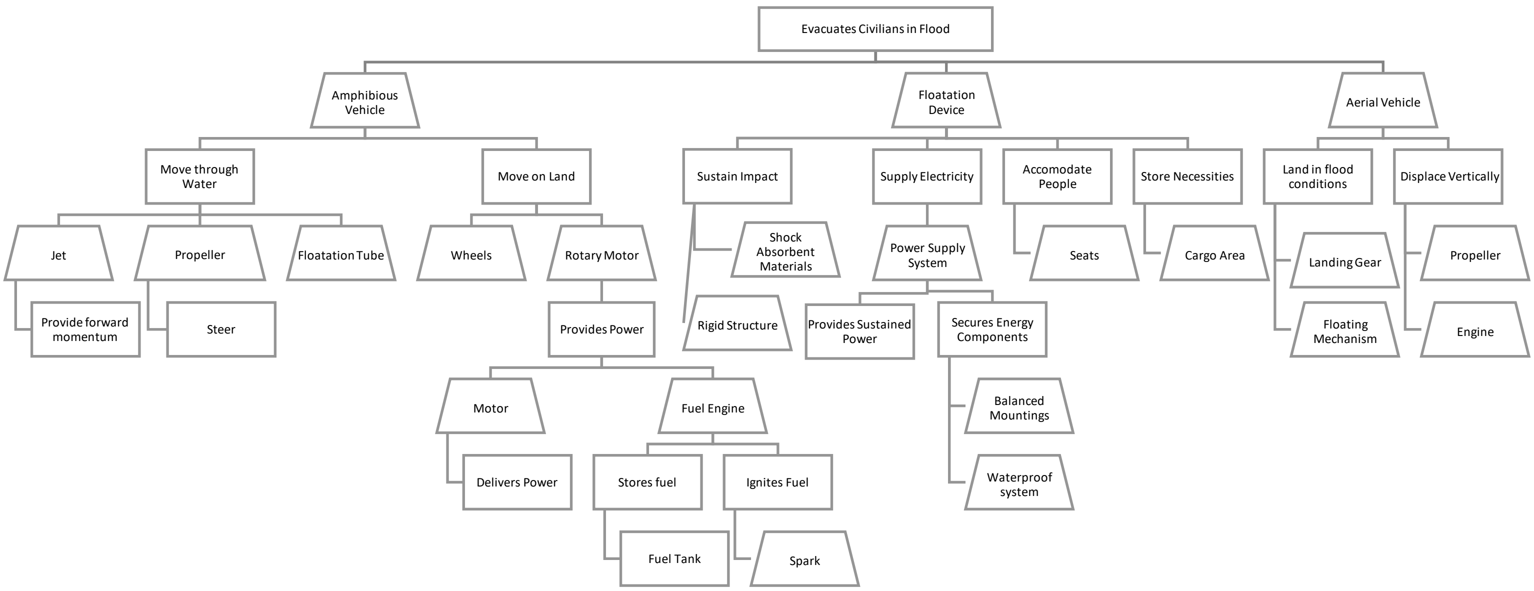


Figure D1. Function Means tree for diverse concepts

E. Morph Chart

Functions	Means		
Move through Water	Jet	Horizontal Propeller	Floatation tube
Move on Land	Wheels	Rotary Motor	
Sustain Impact	Shock absorbent materials	Rigid Structure	
Supply Electricity	Battery	Solar panels	
Accommodate People	Seats	Harness	
Store Necessities	Cargo area	Containers	
Land in flood conditions	Landing gear	Floating mechanism	
Displace vertically	Vertical Propeller	Engine	

Figure E1. Morph Chart of the design space

F. Pugh's Matrix

	Criteria	Importance	Alternatives		
			Amphibious Vehicle Transformation	Flood Adapted Life Raft	Flood Navigation Suit
1	Smooth Ride in flood waters	8	Datum	-	-
2	Navigable in various flood conditions (deep, shallow, land)	10		-	+
3	Efficient in evacuation of users	20		-	-
4	Low-cost	15		S	S
5	Accessible to various sized households	10		S	+
6	Safe	20		+	-
7	Easy to manufacture	11		S	+
8	Water corrosion resistant	7		+	+
		Total +	-	2	4
		Total -	-	3	3
		Overall Total	-	-1	1
		Weighted Total	-	-11	-10

Figure F1. Pugh's Matrix for Concept Selection

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