Cart Motorisation Device (CMD)

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Executive Summary

This report details the process of designing and producing the Cart Motorisation Device (CMD) which can be used to provide propulsion assistance during the use of beach carts and wagons. The process includes various methodologies ranging from marketing and design conceptualisation to project planning and cost calculations.

The Marketing analysis initiated the process and revealed several key findings related to the CMD. Firstly, it was established that the market for beach carts has a segment that the CMD can compete in. This market segment has an annual revenue of USD 80 million and provides a justifiable case for producing and selling the device. Secondly, the CMD must be sold as a more affordable alternative to powered beach carts. And lastly, sales volumes of ca. 6,000 units should be targeted.

This requirement for affordability required a simple and robust design, resulting in the selection of mechanical and electrical technologies that are most conventional. To achieve this most design choices relied on DIN EN ISO standards. In addition to meeting the standard requirements of providing sufficient power (> 200W) and being able to traverse gentle slopes, the device has been designed with supplementary features.

The CMD, along with being battery-powered, is further equipped with a spring system transferring vertical forces from the cart to the wheel via the frame. These vertical forces on the wheel press it onto the ground, hence providing essential traction. To assist in rigidity, 3 clamps facilitate strong connection to the cart at 3 points of contact. 2 of the clamps have hinge connections which allow relative rotation of the device to the cart - necessary for proper function of the spring and very useful in the case of uneven terrain. The clamps are operated using easy-to use hand fasteners - therefore no tools are required to attach the CMD to the cart. Overall, the device is robust and light, weighing only 5.9kg while still being powerful with a 400W motor.

These supplementary features were included because the design process considered many possibilities of design failure. Along with the mechanical design features, electrical design considerations were made to avoid failure during use. The functional structure for the electrical components is a network of components designed to ensure smooth operation. For example: an emergency stop button for safe operation, a high-resolution throttle for effective speed control, and a fuse box to prevent damage caused by overheating.

Furthermore, this design process resulted in the inclusion of an ergonomic user interface that compliments well how the device operates. The interface crucially highlights the charge level and temperature of the battery with a simple 3 LED Module (Green Yellow Red). All these features, from the electrical to the mechanical, made the

design more tangible by specifying real-life parts and technologies that can be used to make the device a product ready for the market.

Once all technologies were designed and specified, methods of production were formulated. Here it was vital to decide on a production quantity of 7,000 units as this meets the sales requirement and provides enough buffer stock. The methods of manufacturing therefore had to achieve this production volume by achieving a takt time of ca. 13 minutes.

Processes such as Laser Cutting, Injection Molding and Gear Hobbing were all designed in a way that produced a unit of the CMD in less than 13 minutes. Machine numbers were selected in accordance with this restriction while some processes were combined to ensure wait times between production stations are not long. This setup resulted in the need for 15 employees to produce the required production volume and it was also determined to be the most cost-effective way to manufacture the CMD.

The importance of affordability, as stated earlier, was further exemplified in the cost calculations of the CMD. Various estimation tools were used that determined the price of the CMD to ultimately be 1,170.81€ (USD 1,205.67), a reasonable option compared to powered beach carts.

Keywords: battery-powered, spring system, DIN EN ISO, hinge connection, affordability, robust, safety

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Milestone 3

1 Marketing Decisions

1.1 Market Findings

The global beach carts market is a sizable market that has shown steady growth since its inception. Its growth trend was disrupted between 2019 and 2021 due to the COVID-19 Pandemic lockdowns that restricted people from going to the beach (among other areas). Figure 1 below provides a snapshot of this growth.

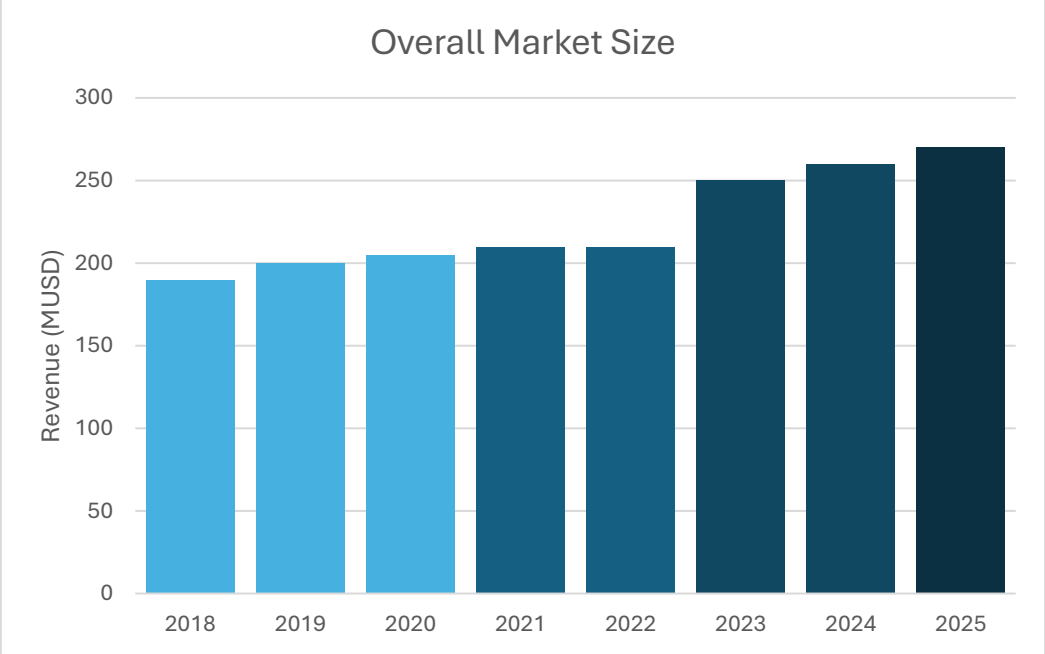


Figure 1 - Global Beach Carts Market Revenues Trend [1]

The market for beach carts had global revenues in 2023 of USD 250 million. Experts believe that this market will show a compound annual growth rate of 5 – 6% from 2023, meaning that modest forecasts for 2024 and 2025 reveal revenues of USD 260 and USD 270 million respectively [2]. The bulk of these earnings are earned in the North American region. Figure 2 below shows the regional segmentation of the beach carts market.

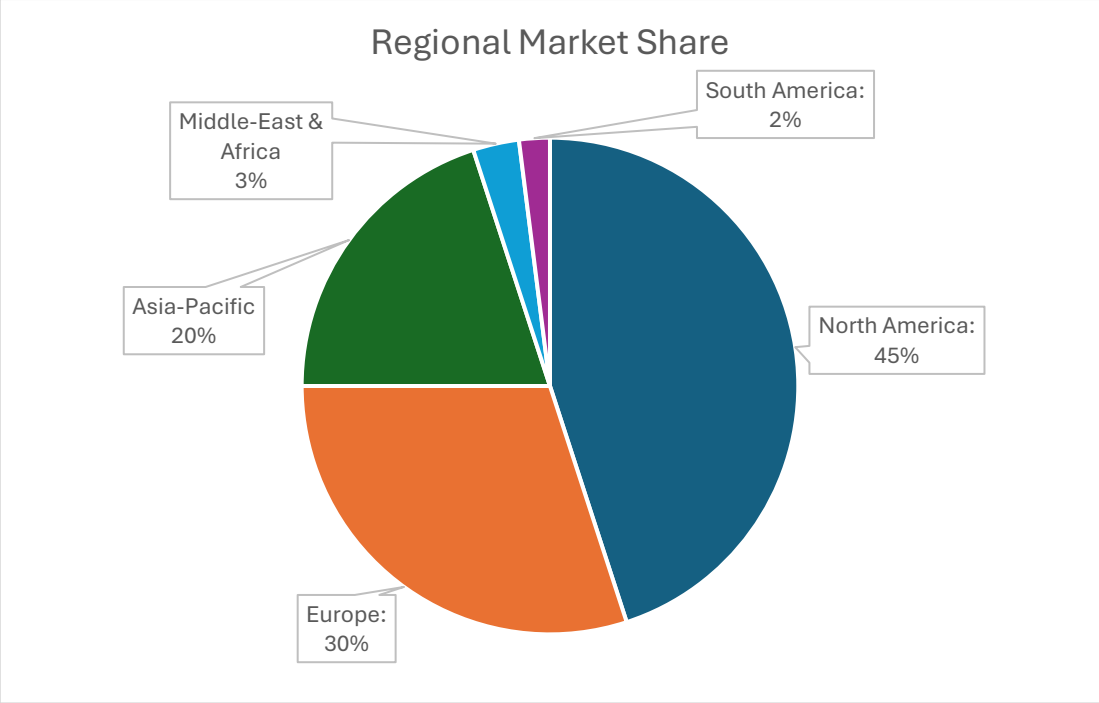


Figure 2 - Regional Beach Carts Market sizes [3]

Further illustration will be provided later in the report, but it must be mentioned now that this market is almost predominantly dominated by non-powered beach carts with a total market share in 2023 of 85-90% [2]. Thus, leaving powered beach carts with a market share of 15% or less, a percentage that cannot be expected to increase dramatically soon. This small share of the market is, as expected, dominated by the North American market, disproportionately so in fact. This stems from the unique "outdoor culture" present in North America. Other regions, including Europe, have an outdoor culture that is not particularly interested in powered beach carts.

In the powered beach cart market, battery-powered electric motors are exclusively the technology used as a propulsion system. Some more niche products also use solar panels to power this system, but the battery powered electric motor is dominant in this segment [1].

This powered beach carts market contains firms providing general outdoor & recreational equipment and firms solely focused on powered beach carts. Table 1 below shows the top 5 companies in the powered beach carts market:

Company Name	Price (USD)	Estimated Market Share
The Beach Mule [4]	950 - 1, 650	High
Wheeleez Inc. [5]	2, 250.00	Moderate to High
Kahuna Outfitters [6]	2, 995.99	Moderate to Low
E-Beach Wagon [7]	2, 499.00	Moderate to High
CaddyTek [5]	2, 100.00	Moderate

Table 1 - Top Suppliers in the Powered Beach Carts Market

**The market shares have been estimated here because the beach carts market is composed of companies that are not publicly listed, meaning more granular data on this market is hidden behind a paywall. Therefore, the estimations above were deduced from the analysis of customer reviews and online blog posts.*

In 2023 an estimated total of 1.47 million units of beach carts were sold globally (powered and non-powered). The predominant buyers were private individuals.

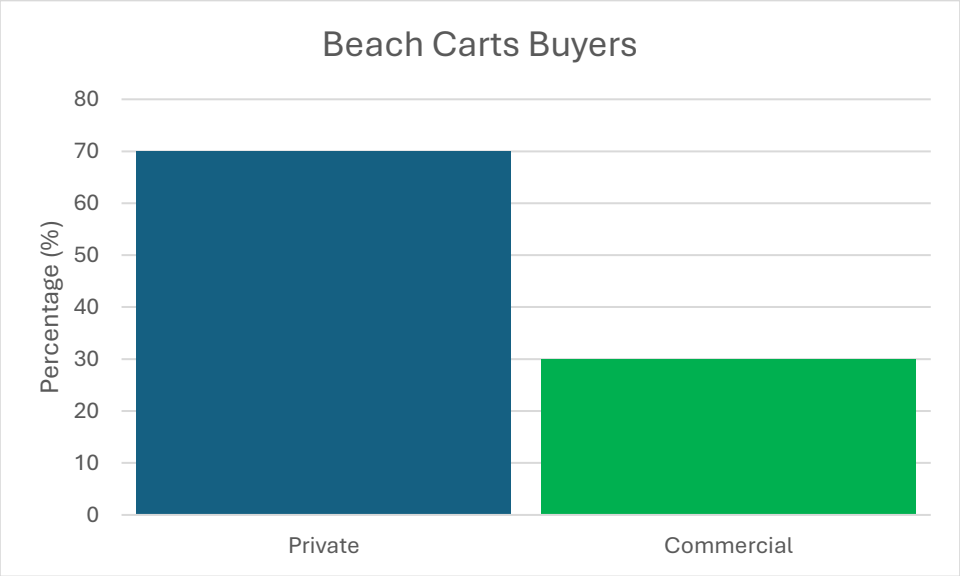


Figure 3 - Beach Carts market by type of buyer

**Commercial use is a broad term that not only includes private companies, but also governmental entities and non-profit organisations.*

1.1.1 Buyer Profile - Private Users

Private individuals fit the expected trend of purchasing a single beach cart (with the exceedingly rare exception of 2 or more units). These individuals are middle-class with enough disposable income to afford a powered beach cart, and the time to indulge in

recreational outdoor activities [8]. They are made up of families with an ingrained culture of maximising on a beach outing or otherwise. This category of private buyers is followed by individuals who are outdoor enthusiasts: campers, surfers, hunters etc. And once both categories have been accounted for, the small remainder of powered beach cart buyers is made up of mostly individuals with mobility issues [8].

It should be noted here that private buyers, regardless of income, are noticeably price sensitive. Meaning that suppliers in this market should prioritise affordability, especially since the alternative, non-powered beach carts, can cost as little as USD 100.

1.1.2 Buyer Profile - Commercial Users

Commercial buyers of beach carts exhibit a completely different buying profile when compared to private users. These entities tend to purchase beach carts in large quantities with the quantity purchased dependent on the type of industry.

Outdoor Recreational Activity Equipment retailers make up the category of commercial buyers and use both online and physical stores to sell these carts. The next industry with a history of purchasing beach carts in large quantities: the hospitality industry, particularly resorts & hotels and rental services [9]. Closely behind these companies are coast guard services, national parks and non-profit organisations assisting individuals with disabilities and mobility issues. Commercial buyers do not typically purchase powered beach carts, one of the reasons why this market segment is smaller than its counterpart.

1.1.3 Foldable vs non-foldable

As a result, companies make decisions on how best to design a beach cart that is both useful and affordable, an endeavour that leads to diverse and unique designs. However, even these unique designs have common elements that allow categorisation, resulting in various categories being used to group beach carts together: material used, wheel type etc, but what is important for this analysis is the product type: foldable or non-foldable. Foldable is the more popular type due to its convenience, easy portability and lower price tag and has a global market share of 60-65%.

For the purposes of marketing this motorisation device, the focus will be on the non-foldable beach carts (35% of the market) since this category of beach carts works with the device. Foldable frames do not allow for power transmission.

1.2 Marketing Approach

As alluded to earlier, the target customer for this device will be any holder of a non-powered beach cart produced with a rigid and non-foldable frame. Based on the market findings, this group of customers can be expected to be 30% of the entire global beach carts market. This means in 2025 the device will be sold in a market segment with revenues of ca. USD 80 million. And to capitalise on this market segment the 4Ps of marketing will be employed: Product, Price, Place, and Promotion [10].

1.2.1 Product

The device will be promoted as an affordable and easy to use product that makes hauling a heavy load easy and light. And even though it is a beach cart accessory, its primary competitors will be powered beach carts. This makes the device a disruptive innovation in the powered beach carts market segment, as it has the potential to make the powered beach cart obsolete as a product. This can be seen in the fact that this device will be marketed in a segment twice the size of the entire powered beach carts market segment but will offer the same functionality and at a lower price.

Furthermore, the comparable functionality that the CMD offers will be complimented by adequate safety features, ergonomic controls, long-lasting battery life and a charging option. All these attributes will be housed in a frame universally attachable to most non-foldable frames. And to further boost consumer confidence and satisfaction, a warranty of 1 – 2 years will be targeted that also includes customer support service. With this service applicable to both retail and wholesale purchases.

1.2.2 Price

The disruptive effect of this device is compounded by its ability to offer powered beach cart functionality at a significantly lower price. A penetration pricing strategy will be employed here to significantly undercut the competition and appeal to owners of non-powered beach carts.

Based on the previous market findings and the desired marketing goal, the following prices will be targeted for the motorisation device:

Type of Purchasing	Amount (USD)
Retail	650
Wholesale	600

Table 2 - Motorisation Device Prices

These prices will be maintained in the initial year of selling, 2025, and following a review of that year's sales, further considerations will be made on the most appropriate pricing strategy.

It will further enhance the marketing of the CMD to include value offers and discounts for potential customers. As a newly developed product in this market, the CMD will initially be released at a discounted price to attract the attention of customers (particularly retail buyers) These will be limited time discounts that help generate interest upon release. Based on market trends, discounts of 5 - 20% will be applied [11], depending on the season of the year. And to boost the efficacy of these discounts, bundle offers are also necessary. More will be elaborated on in the promotional section of this marketing strategy, but suffice it to say here, a discount pricing strategy will also be used when the CMD is bundled with other accessories and or beach carts.

The prices in Table 2 above are meant to serve as long-term anchoring prices that show customers the affordability of the CMD versus the competition of powered beach carts. In the future, these prices will be increased, but the underlying message of affordability will be maintained by always pricing the device below what the competition will have to offer. And nowhere will this message be better communicated than to wholesale buyers.

For commercial buyers, who will make up wholesale purchases, the main reason for purchase is to eventually lease out these devices (resorts, travel agencies, coast guard services etc). Therefore, this customer base will benefit from bulk order discounts when purchasing. The pricing strategies mentioned previously will also be applied to this type of buyer and in addition, the following offers will be available:

- 4% Discount for Prepayments
- 2% Discount for Payments within 2 weeks of ordering
- 3-month payment plan for orders above 100 (at 0% interest)

1.2.3 Place

The strategies outlined here will mainly be applied in the North American region where visibility of the CMD will be most beneficial. Efforts will also be made in other regions (such as Europe) at a scale in proportion with the respective market size of the region.

These placement strategies are outlined as follows:

Social media and Influencers: Using social media platforms and message boards (Instagram, Reddit etc) to reach outdoor enthusiasts, leveraging hashtags and SEO tactics to further boost engagement. In addition, collaborations can be made with prominent relevant content creators to place the product in their content e.g. YouTube ad reads. More of this aspect will be elaborated on in the next chapter, Promotion.

E-commerce and Direct Sales: It is beneficial for this device to have its own website where customers can directly purchase a unit. This will be a direct-to-consumer platform that handles online retail purchases directly made to the supplier. And concurrently, this platform will be supported by partnerships with popular online retailers such as Amazon and Walmart, who already account for over 40% of all beach cart purchases [3].

A separate direct to business online platform will be set up that also allows businesses to directly order from the supplier. Here, focus will be on technical specification and order fulfilment.

Retail Partnerships: This includes all partnerships with physical retailers. Walmart is also included here but these retailers will mostly include sporting goods shops and specialty outdoor retailers. These partnerships are crucial because, as a newly developed product, customers will most likely wish to examine the CMD before deciding to purchase. These partnerships may also include in-store displays and demonstrations that guide and encourage potential customers.

Strategic Trade Shows and Demonstrations: This aspect of the placement strategy is mainly to appeal to commercial buyers. Therefore, outdoor and hospitality trade shows will be targeted to display the efficacy of the device and how useful it is as a product in their businesses. Showcasing the device at relevant events, such as outdoor recreation shows and hospitality trade expos. Live demonstrations at these events allow buyers to experience the device's functionality firsthand.

Distributor Networks: Building relationships with regional distributors who can handle sales in specific markets, especially markets where there's high beach tourism. Incentives for these distributors will be used to promote the device, such as offering commission bonuses for bulk sales or exclusive distribution rights in specific locations.

1.2.4 Promotion

Once again, the strategies detailed here will mainly be applied in the North American region and scaled respectively for other regions.

Digital Marketing Campaign: Running targeted ads on social media sites (Instagram, Facebook) and focusing on key demographics (families, outdoor enthusiasts) and relevant sub-cultures. YouTube advertisements will be coupled with product placement campaigns with outdoor and recreational activities channels. These video creators will offer links and discount codes to the CMD's online platform.

Message boards such as Reddit are a good location for generating discussions around the product. Therefore, the CMD and related content will be posted here to not only promote the product, but to also create a database for product reviews and product development ideas.

Seasonal Promotions and Bundle Offers: As mentioned earlier, discounts of 5 – 20% will be used to promote the product. As this market is seasonal, a strategy will be

implemented that offers higher discounts in peak seasons (e.g. summer) and lower discounts in off seasons (e.g. winter).

This promotional pricing will be further encouraged by bundle offers where the CMD will be sold with beach carts already on the market or with extra parts. Bundle offers will be strongly emphasised for holiday goers as such a promotion allows collaboration with a diverse group of companies.

Partnerships with Retailers and Resorts: Partnering with outdoor equipment retailers and beachside resorts to cross-promote and place the device in relevant environments. This also helps commercial buyers see its efficacy in action. These partnerships also have the possibility to allow the CMD to be paired with already established manufacturers of non-foldable and non-powered beach carts.

Rental Service Collaborations: Working with beach rental services to feature the device, making it available for trial use. Offering a first-time use discount to build loyalty with customers.

Loyalty Program and Referrals: For private buyers, this involves implementing a referral program to encourage word-of-mouth marketing by offering loyalty rewards to customers who refer friends or make repeat purchases.

Targeted Advertising and Content Marketing: Using LinkedIn, trade publications, and online forums specific to the hospitality and outdoor recreation sectors to reach commercial buyers. Case studies and testimonials will be made highlighting how existing commercial users (e.g., resorts, beach rental services) have benefited from the product. Then positioning these stories in relevant B2B publications or websites frequented by potential buyers.

1.3 Expected Sales

Quantity	Amount
Target Market Segment Size	USD 80M
Assumed Market Share	5% (USD 4M)
Selling Price	USD 650
Expected Sales	6, 200 units

Table 3 - Sales Projections

The target retail selling price will be USD 650, which competes well against powered beach carts that typically cost well above USD 1,000. Using this price and assuming an initial market capitalization of ca. 5%, it is reasonable to expect to sell 6,200 units in 2025. Therefore, an initial production volume of 7,000 units will be targeted to also allow for a buffer stock of 800 units.

2 Overall Product Concept

2.1 List of Requirements

1. **Speed Range:** The cart should reach up to 5km/h with smooth acceleration and deceleration, controlled by a throttle.

2. **Load Capacity:** Capable of transporting a maximum load of 75 kg.

3. **Run Time:** Provide at least 1 hour of continuous operation on a full charge.

4. **Torque for Take-Off:** Sufficient starting torque to move from a standstill with a full load on flat and slightly inclined surfaces.

5. **Emergency Stop:** An immediate cut-off switch, located at the cart handle to stop the motor in emergencies.

6. **Overcurrent Protection:** A fuse to prevent excessive current that could damage components.

7. **Thermal Management:** Sensors to monitor and prevent overheating of the motor and battery.

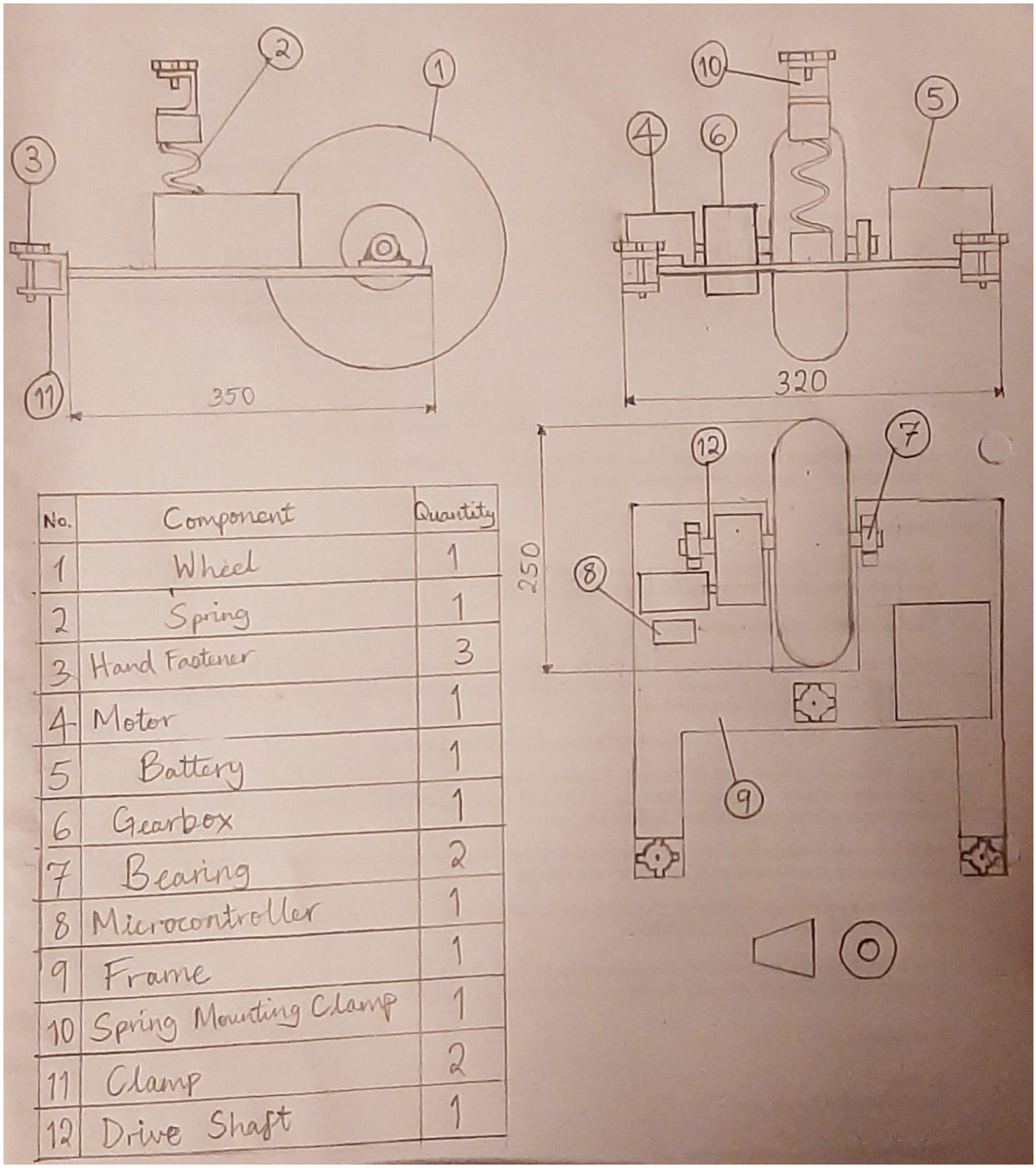
8. **Battery Management:** Integrated BMS (Battery Management System) for overcharge, over-discharge, and short-circuit protection.

9. **Compact and Lightweight Design:** Total weight under 6 kg for easy handling and transport.

10. **Quick Assembly and Disassembly:** Modular design with quick-release mounts for attaching or detaching the motor unit from the cart.

11. **Water and Dust Resistance:** Basic protection (such as IP rating of IP54) to prevent damage from dust and light splashes.

12. **Durability:** Frame and components should withstand normal wear and tear over long-term use, especially with frequent loading and unloading.



No.	Component	Quantity
1	Wheel	1
2	Spring	1
3	Hand Fastener	3
4	Motor	1
5	Battery	1
6	Gearbox	1
7	Bearing	2
8	Microcontroller	1
9	Frame	1
10	Spring Mounting Clamp	1
11	Clamp	2
12	Drive Shaft	1

Figure 4 - CMD Concept Sketch

The main components of the device include: the frame, the wheel, the brushed DC-motor, the battery, the microcontroller, and the interface (controls). The idea is to attach our device to the back of the cart. Once attached, the user can use the interface (buttons and throttle controls) to turn the motor on or off and to control the velocity of the cart. Electrical energy is provided to the DC-motor by a battery. The motor then supplies a torque to the wheel which propels the cart forward. The User steers the cart via the handlebar.

Function	Sub-function	Option 1	Option 2	Option 3
Motion	Motor type	Electric motor	Small internal combustion engine (ICE)	Pneumatic motor
	Speed control	Pressure regulated valve	Variable speed throttle	Hydraulic flow control
Frame design	Frame material	Lightweight aluminium	Reenforced steel	3D printed composite (carbon fibber or PLA)
	Suspension	No suspension (rigid frame)	Basic spring suspension	Magnetic suspension
Fuel and energy	Fuel source	Compressed air canister	Gasoline tank	Rechargeable battery
	Refuelling/Charging Method	Standard gas station	Plug-in electric charging	Compressed air refill station
User interface	Throttle design	Thumb-twist speed control	Touch sensitive slider	Lever-based speed control
	Feedback mechanism	Digital display with diagnostics	Sound based alert system	LED indicators for speed and fuel/battery

Table 4 - CMD Morphological Box

3 Functional Structure

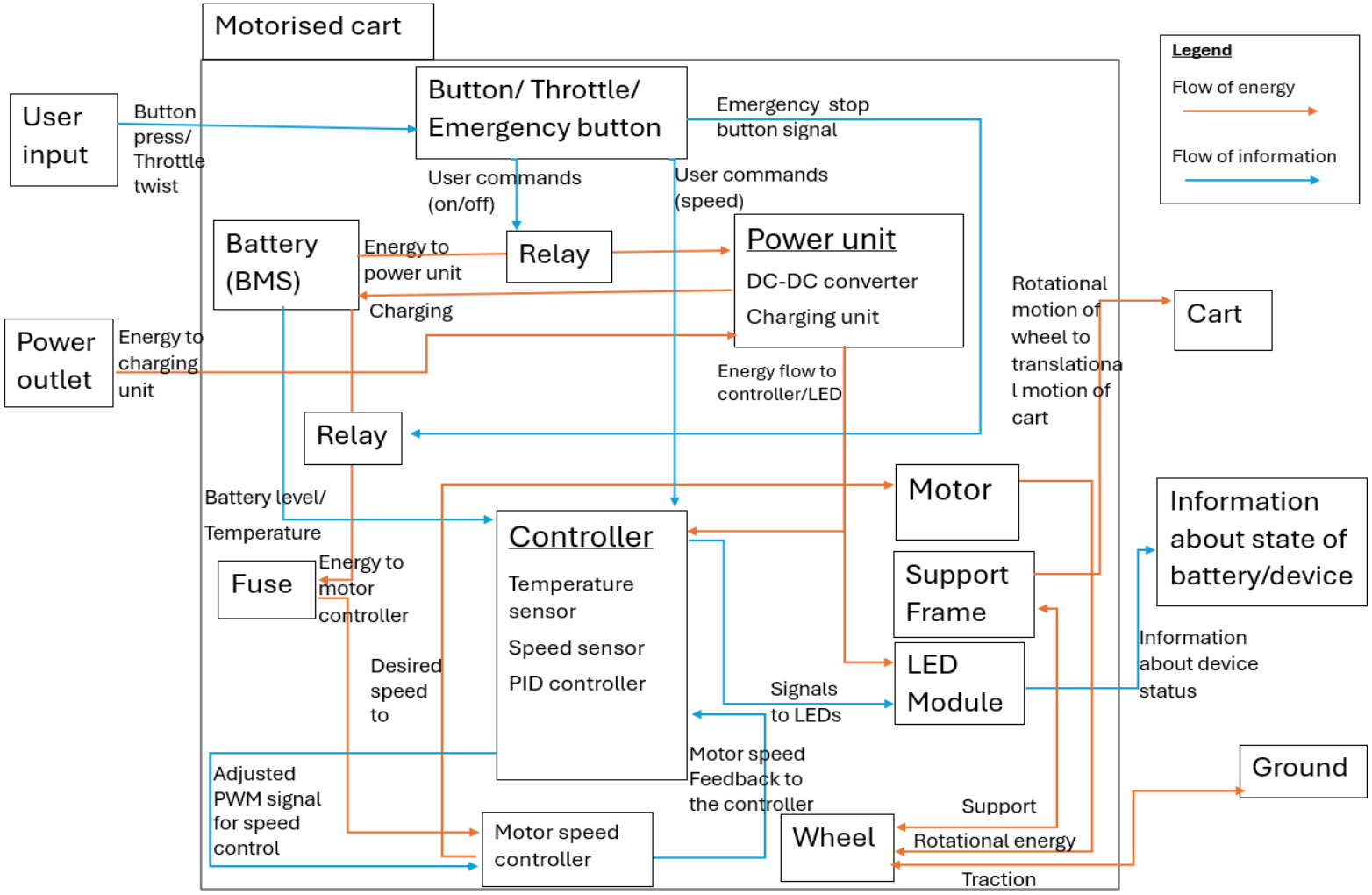


Figure 5 - CMD Functional Structure Diagram

3.1 Working Principles

1. **Power Source and Distribution:**

    - **Battery (BMS):** The Battery Management System (BMS) manages the battery's energy level, monitoring for overcharging, discharging, and temperature protection. It supplies power to the Power Unit and receives charging energy when connected to an external power outlet.
    - **Power Unit:** This module consists of a DC-DC converter and charging unit, it regulates power distribution to other components such as the controller, LED module, and motor speed controller. It ensures stable voltage levels and supplies energy when needed, while also receiving input for charging the battery.

2. **Control and Safety Mechanisms:**

    - **Button, Throttle and Emergency Button:** The button allows the user to power the device on/off via a relay. The throttle allows the user to control the cart's speed by sending user input signals to the controller. The emergency stop button is connected to a relay, which can cut off power to the motor in emergencies, ensuring immediate shutdown.
    - **Relay:** The relay acts as a physical power cut-off mechanism when the emergency button is activated, disconnecting the power flow to the motor, overriding all other signals, and ensuring safe operation.

3. **Controller and Sensors:**

    - **Controller:** This is the central processing unit with a PID controller for speed regulation. It processes user commands from the throttle, as well as feedback from the speed sensor and temperature sensor, to manage the motor's operation. It calculates the desired speed and sends PWM signals to the motor speed controller for precise speed control.
    - **Sensors:**
        - Speed Sensor provides real-time speed data to the controller, enabling the PID controller to adjust motor power and match the desired speed set by the throttle.
        - Temperature Sensor monitors critical areas like the motor and battery, sending information to the controller to prevent overheating by adjusting performance or shutting down if limits are exceeded.

4. **Motor Speed Control and Motion:**

    - **Motor Speed Controller:** This component receives the PWM signal from the controller and adjusts the motor's speed accordingly. The motor speed controller manages the power delivered to the motor, allowing for controlled acceleration and deceleration.
    - **Motor and Wheel:** The motor converts electrical energy into mechanical rotational energy, which is transferred to the wheel. The rotation of the wheel generates translational motion, moving the cart forward. The controller adjusts the motor speed based on the PID controller feedback, keeping the speed consistent with the user's input.

5. **LED Module:**

    - The LED Module provides visual feedback to the user regarding the system's operational state, such as battery status, and fault warnings. It receives signals from the controller, ensuring that the user is always informed of the system's status.

6. **Support Frame:**

    - **Support Frame:** Holds all the components. It connects the motor to the wheel and cart.

4 Drive Concept

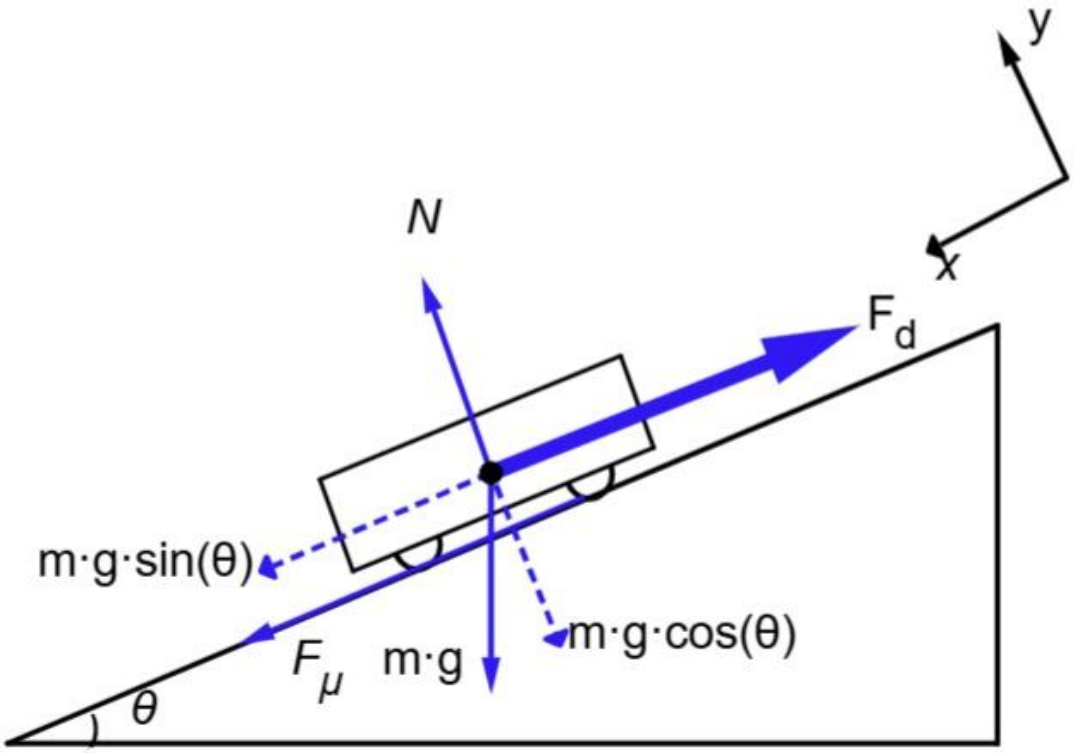


Figure 6 - Free Body Diagram of the CMD and Cart

Assuming the following:

- Total mass of the cart and the load (m) = 75kg
- The rolling coefficient of friction (μ) = 0.012
- Gravitational Acceleration (g) = 9.81 m/s²
- Operational Time (t) = 1 hour
- Maximum Velocity (v) = 5 km/h ≈ 1.39m/s
- Angle of incline (Θ) = 5.7°
- Required acceleration (a) = 0.347m/s²

The following was computed:

Flat Surface Driving Force:

$$Driving\ Force,\ F_d = (m \times a) + (m \times g \times \mu), \therefore F_d = (75 \times 0.695) + (75 \times 9.81 \times 0.012) \approx 35N$$

Inclined Surface Driving Force:

$$Driving\ Force, F = (m \times a) + (m \times g \times cos\theta \times \mu) + (m \times g \times sin\theta) = (75 \times 0.695) + (75 \times 9.81 \times \cos 5.7^o \times 0.012) + (75 \times 9.81 \times sin 5.7^o) \approx 108N$$

Therefore, the maximum required power (P):

$$P = F_d \times v = 108 \times 1.39 \approx 150W$$

Motor technology:

Brushed DC Motor (BDC) - it is simple control, has a high starting torque, and is affordable

Battery technology:

Lithium-Ion (Li-ion) - It has a high energy density, long cycle life, and is lightweight

5 D-FMEA

Rating	**S**everity of Effect	**P** (Failure Probability)	**D**etectability
1	No impact	Extremely Low	Almost certain
2	Minor Inconveniences	1 out of 1,000,000	Very high
3		1 out of 100,000	High
4		1 out of 10,000	Moderate High
5	Loss of Secondary functions	1 out of 2,000	Moderate
6		1 out of 500	Moderate Low
7	Loss of Primary functions	1 out of 100	Very Low
8		1 out of 50	Unlikely
9	Issue of Security and/or compliance regulations	1 out of 20	Very unlikely
10		More than 1 out of 10	Almost impossible

Table 5 - DFMEA Rating Table (Derived from the Norm standard, DIN EN 60812)

	Initial state								Revised state				
	Function	Potential failure mode	Potential effects of failure	Potential causes	S	P	D	RPN	Actions taken	S	P	D	RPN
Motor	Convert electrical energy into mechanical energy	**Over function** Overheating	Permanent damage to internal motor components like windings; reduced efficiency.	Excessive current.	7	5	3	105	Fuse is used in case of overcurrent.	5	2	1	10
				Lack of cooling.	7	4	3	84	Fans are used to cool the motor.	5	2	2	20
				Poor ventilation.	7	3	3	63	There are holes in the casing to allow flow of air.	5	2	2	20
		Malfunction Electrical short circuit	Damage to motor, circuit overload, potential fire hazard.	Insulation breakdown due to:									
				Wear	10	3	3	90	High-grade wiring is used.	8	2	1	16
				Environmental exposure.	10	5	3	150	Housing is IP54.	8	2	2	32
				Manufacturing defects.	10	4	3	120	Several tests are run before product is out.	9	2	2	36
		Under function Bearing Failure	Increased motor vibration and noise; risk of motor misalignment.	Insufficient or improper lubrication.	6	4	3	72	Automated lubrication system added.	3	2	2	12

				Bearing wear.	6	3	3	54	High quality bearings are used.	4	2	2	16
		Under function Contamination (Dust, Moisture, Chemicals)	Reduced motor efficiency, internal corrosion, increased risk of failure.	Inadequate sealing, exposure to contaminants.	6	3	4	72	Sealed motor enclosures and moisture-resistant materials used to prevent contamination.	4	2	2	16
		No Function Motor Control Failure	Loss of motor function or erratic motor behavior.	Faulty or misconfigured controller.	6	3	3	54	Diagnostic checks scheduled and improved controller calibration applied.	3	1	2	6
				Wiring issues.	6	3	3	54	High quality wiring is used.	4	2	2	16
Battery	Accept, store, and release electricity on demand	**No Function** Overheating	Battery life reduction, swelling, risk of leaks or combustion.	External heat.	6	4	2	48	Fans and sensors installed, alerting users if temperature reaches unsafe levels, automated	3	2	2	12

								shutdown installed.				
				Continuous power draw.	6	5	3	90	Battery monitor system installed.	4	2	2	16
				Lack of ventilation.	6	4	3	72	Fans and holes are used in the casing to allow flow of air.	5	1	3	20
		Under function Over-discharge	Reduced capacity, loss of battery life, potential permanent damage.	Leaving the battery in a discharged state for too long.	8	5	3	120	Battery monitoring with low-charge LED alert and auto shutoff installed.	5	2	1	10
		Malfunction Swelling or Gas Build-up	Physical deformation, causing damage, risk of rupture or leaks.	Overheating.	6	3	3	54	Fans and sensors installed, alerting users if temperature reaches unsafe levels, automated shutdown installed.	5	2	2	20
				Internal short circuit	10	2	4	80	High grade wiring and fuse are used.	8	2	2	32

				Overcharging	7	2	4	56	Battery monitor system and fuse installed.	5	2	3	30
		Malfunction Internal Short Circuit	Battery failure, fire, or explosion.	Manufacturing defects	10	2	4	80	Safety tests and high-quality sourcing.	8	2	2	32
Wheel	Enable movement	**Under function** Wheel Slippage	Reduced mobility, impaired control, safety risk.	Insufficient traction or grip.	6	4	3	72	High-traction material implemented.	3	2	2	12
				Overloading of the cart causing excessive slippage.	6	4	3	72	Improved tread design.	3	2	2	12
		Malfunction Wheel Deformation or Breakage	Loss of mobility and function. Potential injury if the wheel fails while cart is in incline.	Excessive load on wheels.	9	3	3	81	Conduct load tests for wheel design.	6	1	2	12
				Impact with rocks or obstacles.	9	3	3	81	Use durable materials	6	2	2	24

		Under function Corrosion of Wheel Components	Loss of structural integrity of the wheel.	Lack of protective coatings.	7	3	3	63	Protective coatings applied to key parts, corrosion checks.	4	2	2	16
				Use of unsuitable materials	7	3	4	84	Corrosion resistant materials are used.	5	2	2	20
		Under function Wheel Assembly Loosening or Detachment	Sudden loss of mobility. Damage to the other components	Vibration or shock from rough terrain.	8	3	2	48	Materials resistant to vibrations are selected.	4	2	2	16
				Loose fasteners or inadequate securing mechanisms.	8	3	3	72	Assembly is tested.	5	2	2	20
	Securely	**Under function** Clamp Slippage or Loosening:	Wheel misalignment or detachment.	Insufficient clamping force due to design or material	8	4	3	96	Friction pads added.	5	2	2	20

Clamps	attach wheels to the cart's rear axle, allowing quick installation without tools	The clamp does not securely hold the wheel, leading to misalignment or detachment.	Damage to the wheel.	Vibration or movement on rough terrain loosening the clamp.	8	4	3	96	Vibration testing performed and materials resistant to vibrations are selected.	6	2	2	24
				Inadequate surface grip between the clamp and axle.	8	3	3	72	The tolerance in the clamp design is small so the user knows when clamps are properly attached.	5	2	2	20
		Malfunction Clamp Breakage: Clamp may break under excessive load, causing the wheel to detach.	Immediate loss of wheel attachment. Injury or damage to surrounding components.	Use of brittle or low-strength materials.	9	3	3	81	Stronger materials used.	6	2	1	12
				Excessive load or impact on the clamp, especially on rough terrain.	9	3	3	81	Load testing performed	6	2	2	24
		No Function Difficulty in Quick Attachment/ Detachment:	Increased time required for assembly. Frustration or user error in attachment,	Misalignment between the clamp and axle.	5	3	3	45	Design updated to allow easier attachment and removal.	3	2	2	12

		Difficulty in installing or removing the clamp, leading to delays or frustration.	reducing clamp security.	Obstacle in the attachment mechanism.	5	4	3	60	Design is made such that it is easy to remove obstacles.	4	2	2	16
		Under function Clamp Misalignment	Reduced clamp strength and reliability. Accelerated wear leading to breakage or loosening.	Difficulty in aligning the clamp during attachment.	6	4	3	72	The tolerance in the clamp design is small so the user knows when clamps are properly attached.	3	3	2	18
Wiring	Transmit electrical power and signals between components reliably under varying environmental conditions.	**No Function** Wire Insulation Degradation	Risk of short circuits or electrical fires. Intermittent or complete loss of power to components. Damage to other components due to exposed wiring.	Exposure to hot temperatures, UV.	9	4	3	108	Temperature sensors, fuse and relays are implemented.	6	2	2	24
				Low-quality insulation materials.	9	3	3	81	High grade insulation is used.	6	2	2	24
		Malfunction Loose or Faulty Connections	Intermittent or complete power loss to components.	Vibration from cart movement causing connector	8	4	3	96	Vibration resistant materials are selected.	5	2	2	20

			Reduced efficiency. Sparking or overheating at loose connections, risking fire.	s to loosen.									
				Mediocre quality or improperly sized connectors.	8	3	3	72	High grade wiring is used.	5	2	2	20
				Incorrect installation or insufficient securing of connections.	8	3	4	96	Connections inspected.	7	2	2	28
		Malfunction Overheating	Melted insulation and exposed wires leading to short circuits. Potential for fire if overheating is severe.	Excessive power demands from the motor or other components.	9	3	4	108	Fuse and relays are implemented.	6	2	2	24
				Poor ventilation or lack of heat dissipation measures.	9	4	3	108	Temperature sensors, fans and holes are used.	7	2	2	28

		Under function Electrical Noise or Signal Interference	Degraded performance of speed control or motor response. Potential malfunction of electronic components.	Lack of proper grounding or shielding.	6	3	3	54	Shielded cables are used and proper grounding is included in design.	4	2	1	8
Potentiometer/ Throttle	Control motor speed by adjusting electrical resistance in response to user input.	**No Function/ Under function** Potentiometer Drift	Unstable or inaccurate speed control, potentially causing safety concerns. Increased wear on other components due to erratic power output.	Wear of the resistive element due to frequent use.	8	4	3	96	Durable material is selected.	5	2	2	20
				Exposure to environmental changes, including temperature fluctuations and humidity.	8	3	3	72	Environmental sealing is used.	6	2	2	24
		Malfunction/ No Function Physical Damage from User Misuse:	Loss of control, resulting in unintentional speed changes. Increased wear on components,	Excessive force applied by the user.	7	4	4	112	Durable throttle used.	4	3	2	24

		User may apply excessive force or use the throttle incorrectly, damaging it.	shortening the potentiometer's lifespan.	Lack of user guidance on gentle handling.	8	3	2	48	Clear instructions provided.	7	2	1	14
PID controller	Control motor speed and power output to maintain a stable and user-desired speed, adjusting in response to feedback from sensors.	**Under function** Controller Drift or Calibration Loss	Inconsistent speed control, leading to jerky or unstable operation.	Internal component aging or environmental factors causing parameter drift.	8	4	3	96	High-quality sensors and periodic calibration check integrated.	5	2	1	10
		Malfunction Sensor Malfunction or Feedback Loss	Uncontrolled motor operation, leading to abrupt speed changes.	Sensor failure due to environmental stress (moisture, debris).	9	3	3	81	High-quality sensors are selected which run a redundant feedback loop.	5	2	2	20
Sensors	Provide accurate readings of speed, temperature, battery level,	**Malfunction** Sensor Malfunction or Inaccurate Readings	Inaccurate control response, potentially causing unsafe or inefficient operation.	Internal component failure Calibration drift from vibration, wear, or temperatu	8	4	3	96	High-quality sensors are selected.	4	2	2	16

				re changes.									
		Under function Sensor Response Delay or Latency	Potentially unsafe conditions if adjustments are slow to respond to changes.	Data bottleneck in the system, leading to slow signal processing.	7	3	3	63	Data flow from sensors to controller is optimized and sensors with low response times are selected.	4	2	1	8
Fuse	Protect the electrical system by interrupting excessive current flow, preventing overheating, fire, and damage to components.	**No Function** Fuse Blows Prematurely/ Does not blow at all	Unexpected shutdown of the cart, leading to user inconvenience.	Fuse rating too low for normal operating current.	6	3	4	72	Fuses are evaluated for accurate ratings based on system specifications.	4	2	2	16
				Environmental vibration or temperature fluctuations affecting fuse reliability.	7	3	3	63	High quality fuses are selected.	6	2	2	24

Relay	Control and manage the flow of current between the battery and fuse, and between the battery and power unit, ensuring safe and efficient operation of the cart.	**Malfunction** Relay Contacts Fail to Open	Continuous current flow, potentially leading to overloading of connected components. Increased risk of overheating, potentially causing damage to the battery or power unit.	Contact welding due to excessive current or environmental corrosion.	8	3	3	72	High-quality, high-current-rated relays are used.	6	2	2	24
				Mechanical failure from frequent cycling or vibration-induced damage.	7	4	3	84	Vibration resistant materials are used.	5	2	2	20
		No Function Relay Contacts Fail to Close	Loss of power to the connected load User inconvenience and control loss.	Dirt, sand, or corrosion build-up on contacts.	7	3	3	63	Sealed housing is designed.	5	2	2	20
				Coil failure or mechanical issues preventing proper contact closure.	7	3	4	84	High quality materials are selected.	5	3	2	30
		Malfunction Relay Coil Burnout	The relay fails to operate, causing either continuous power loss or uncontrolled power flow.	Overvoltage or excessive current applied to the coil.	8	2	4	64	Relay coils are chosen for voltage compatibility.	5	3	1	15

			Increased maintenance time to replace burned-out relays.										

Table 6 - The CMD D-FMEA Table

6 Project Plan

6.1 Work Breakdown Structure

Beach Cart Motorisation Device			
KEY: *Electrical Engineer - EE, Industrial Engineer - IE, Mechatronic Systems Engineer - MSE, Mechanical Engineer – ME*			
Deliverable 1	**Marketing Decisions**		
WBS	*Activity*	*Responsible*	*Resources*
1.1	Collect research information	IE	Market Reports, Blogposts, Buyer Reviews
1.2	Analyse market relevant information	IE	Microsoft Excel
1.3	Marketing Strategy Design	IE	Marketing Textbooks, ChatGPT
Deliverable 2	**Overall Product Concept**		
2.1	Analyse List of requirements	ME, IE, MSE, EE	Brainstorming Tools
2.2	Research and assessment of feasible conceptual frameworks	ME	Patents, Similar Product Concepts
2.3	Calculations based on selected concept	ME	MATLAB, Excel
2.4	List of required materials	ME	Brainstorming Tools

Deliverable 3	**Functional Structure**		
3.1	Establishment of device working principles	ME, MSE, EE	Block Diagrams, Engineering Textbooks
3.2	Application of modelling and simulation techniques	EE, MSE	SolidWorks, Simulink
3.3	Finalisation of the functional diagram	MSE	Microsoft Word
Deliverable 4	**Drive Concept**		
4.1	Analysis of all physical requirements e.g. maximum speed	MSE, ME	Brainstorming Tools
4.2	Selection and specification of the necessary drive technology	MSE, EE, ME	Supplier catalogues, electric motor and drives specification tables
Deliverable 5	**D-FMEA**		
5.1	Analysis of results from Deliverables 2 - 4	ME, EE	Relevant templates, Excel, Brainstorming Tools
5.2	Documentation of relevant Data	ME, EE	Sciebo, Google Docs, SharePoint
Deliverable 6	**Project Plan**		
6.1	Definition of the project’s scope	IE	Brainstorming Tools, Project Management Course Notes
6.2	Outlining of work breakdown structure	IE	Project Management Course Notes
6.3	Gantt Chart Creation	IE	Excel
Deliverable 7	**Complete 3D Model**		
7.1	Free-hand sketch according to ISO10209	ME, IE	SolidWorks, Sketching Tools
7.2	CAD Model of all individual components	ME, IE	SolidWorks, Mechanical and Metal Trades Handbook

7.3	CAD Assembly of final product	ME, IE	SolidWorks, Mechanical and Metal Trades Handbook
Deliverable 8	**Motor & Energy Storage Dimension**		
8.1	Requirements Analysis	ME, MSE, EE	Brainstorming Tools
8.2	Selection of Motor and Energy Storage	ME, MSE, EE	Motor & Battery Technical Specifications, Supplier Catalogues
8.3	Design of Power Management System	MSE, EE	Simulink
Deliverable 9	**Human Machine Interface**		
9.1	User Requirements Analysis	MSE, EE	Brainstorming Tools, Sketching Tools, Subreddits, Blogposts
9.2	Interface Design	MSE, EE	Sketching Tools, SolidWorks, UI/UX Design Tools
9.3	Selection of Software and Control Logic	MSE, EE	Python, Microcontroller Specifications, Supplier Catalogues
9.4	Overall System Integration	MSE, EE	MATLAB, System Design Textbooks
Deliverable 10	**Technology Section for “Make” Parts**		
10.1	CAD Design & Modelling	ME, IE	SolidWorks, Mechanical and Metal Trades Handbook
10.2	Material Selection	ME, IE	Material Databases
10.3	Manufacturing processes selection	ME, IE	Manufacturing Process Databases, Technical Literature
Deliverable 11	**Requirements Manual for “Buy” Parts**		
11.1	List of all required components (specified)	ME, IE	Supplier Catalogues, Technical Databases
11.2	Compilation of suitable suppliers	ME, IE	Supplier Research Platforms (e.g. Alibaba)

Deliverable 12	**Technical Drawings for Main Assembly**		
12.1	Finalisation of Components	ME	SolidWorks, Mechanical and Metal Trades Handbook
12.2	Finalisation of Assembly layout	ME	SolidWorks, Mechanical and Metal Trades Handbook
12.3	Dimensioning and Tolerancing	ME	SolidWorks, Mechanical and Metal Trades Handbook
12.4	Compilation of all relevant views	ME	SolidWorks, Mechanical and Metal Trades Handbook
Deliverable 13	**Program Flow Chart**		
13.1	Process Mapping	EE, MSE	Word, Process Mapping Software
13.2	Flowchart Design	EE, MSE	Word
Deliverable 14	**Bill of Materials**		
14.1	Compilation of Component List	ME, IE	Excel, Supplier Catalogues
14.2	Materials and Specification Details	ME, IE	Material Databases, Supplier Data Sheets
Deliverable 15	**Production Planning**		
15.1	Production Process Definition	IE	Process Mapping Tools, Excel, Manufacturing Process Literature
15.2	Scheduling & Staffing Calculations	IE	Gantt Charts, Excel
15.3	Inventory Management System Design	IE	Excel
Deliverable 16	**Cost Calculation**		
16.1	Costing Analysis Selection	IE	Excel

16.2	Direct Manufacturing Cost Calculations	IE	Excel
16.3	Overhead Cost Calculations	IE	Excel

Table 7 - CMD Project Plan

6.2 Network Diagram

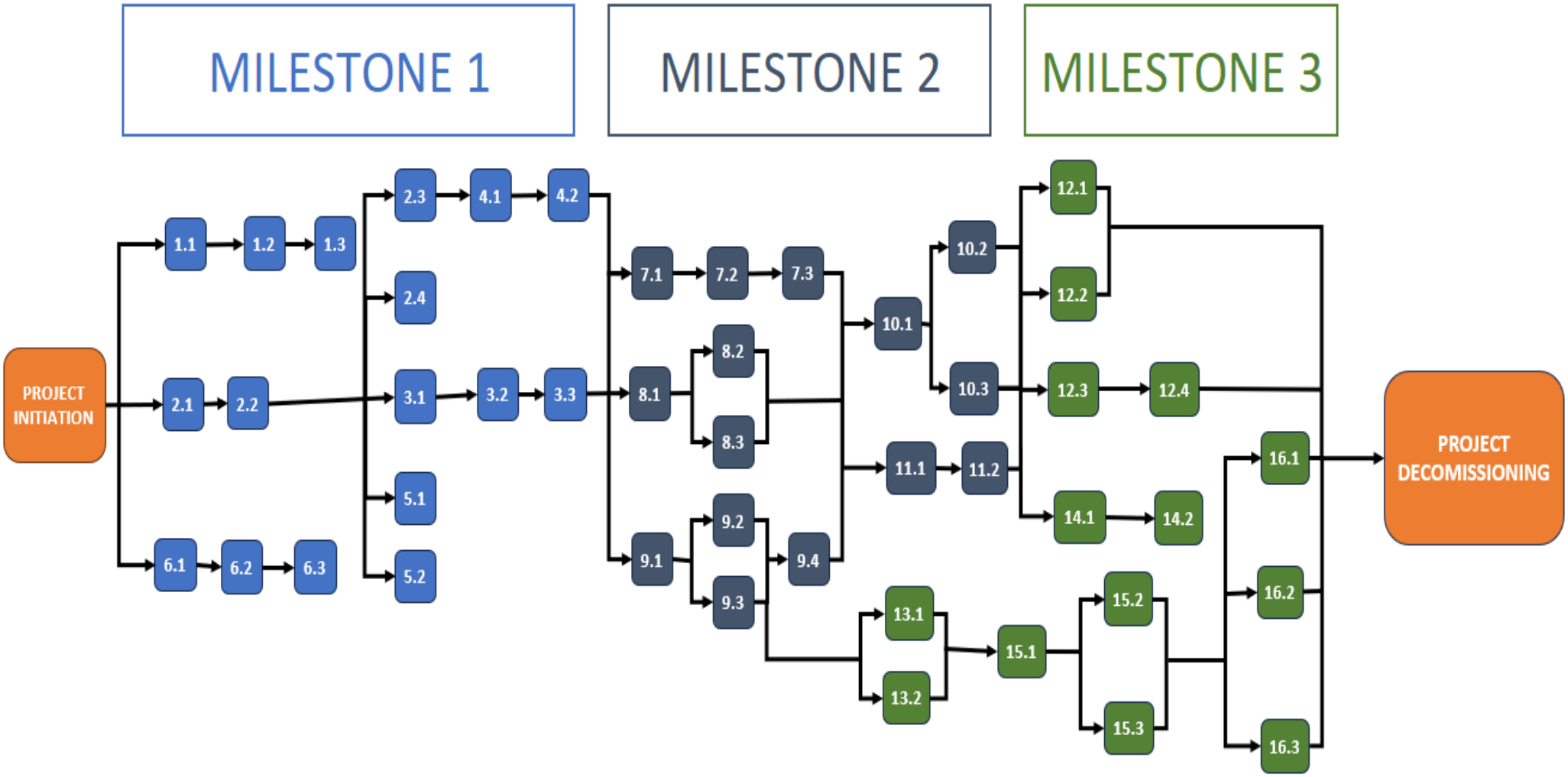


Figure 7 - CMD Network Diagram

6.3 Gantt Charts

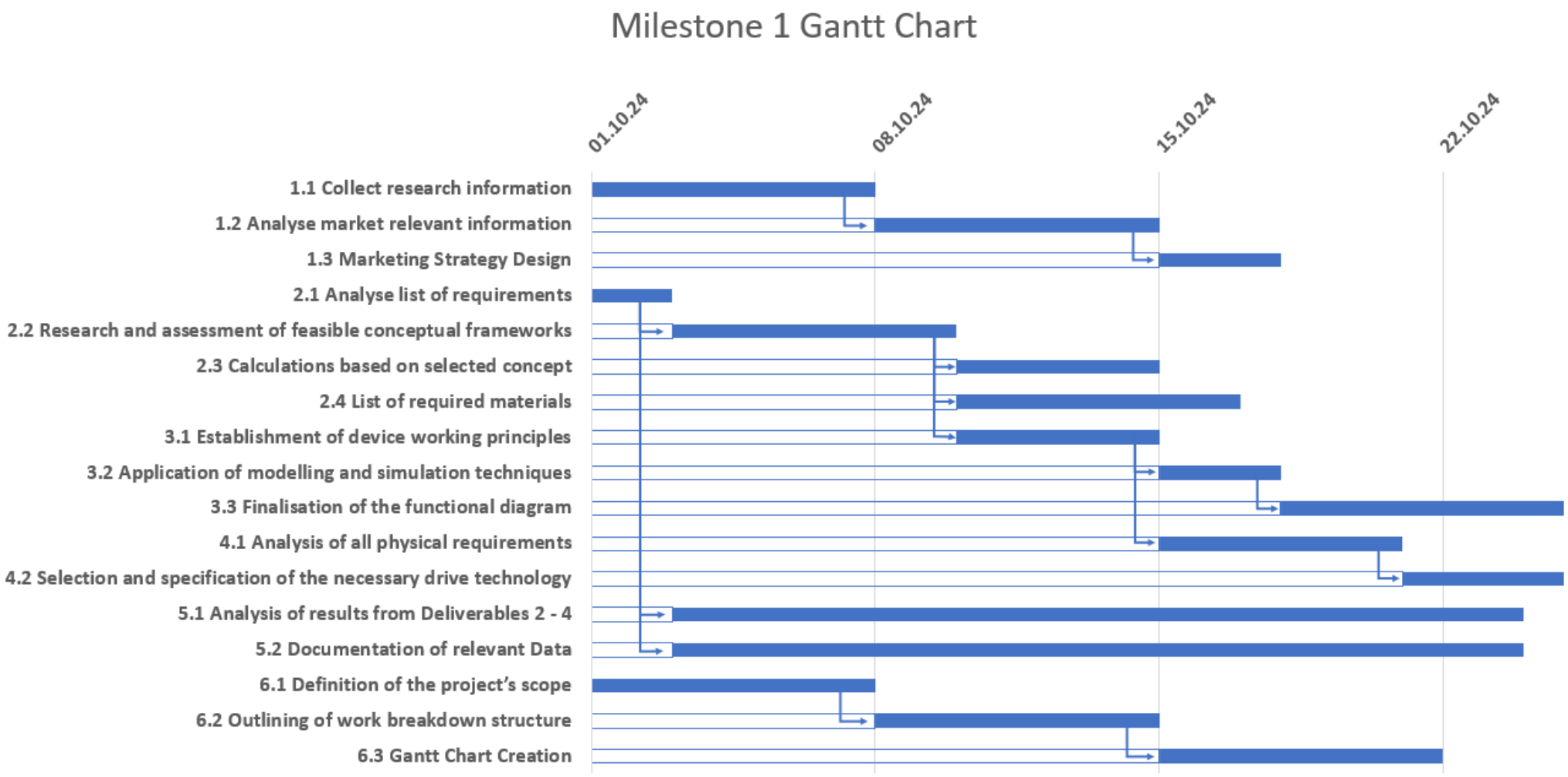


Figure 8 - Milestone 1 Gantt Chart

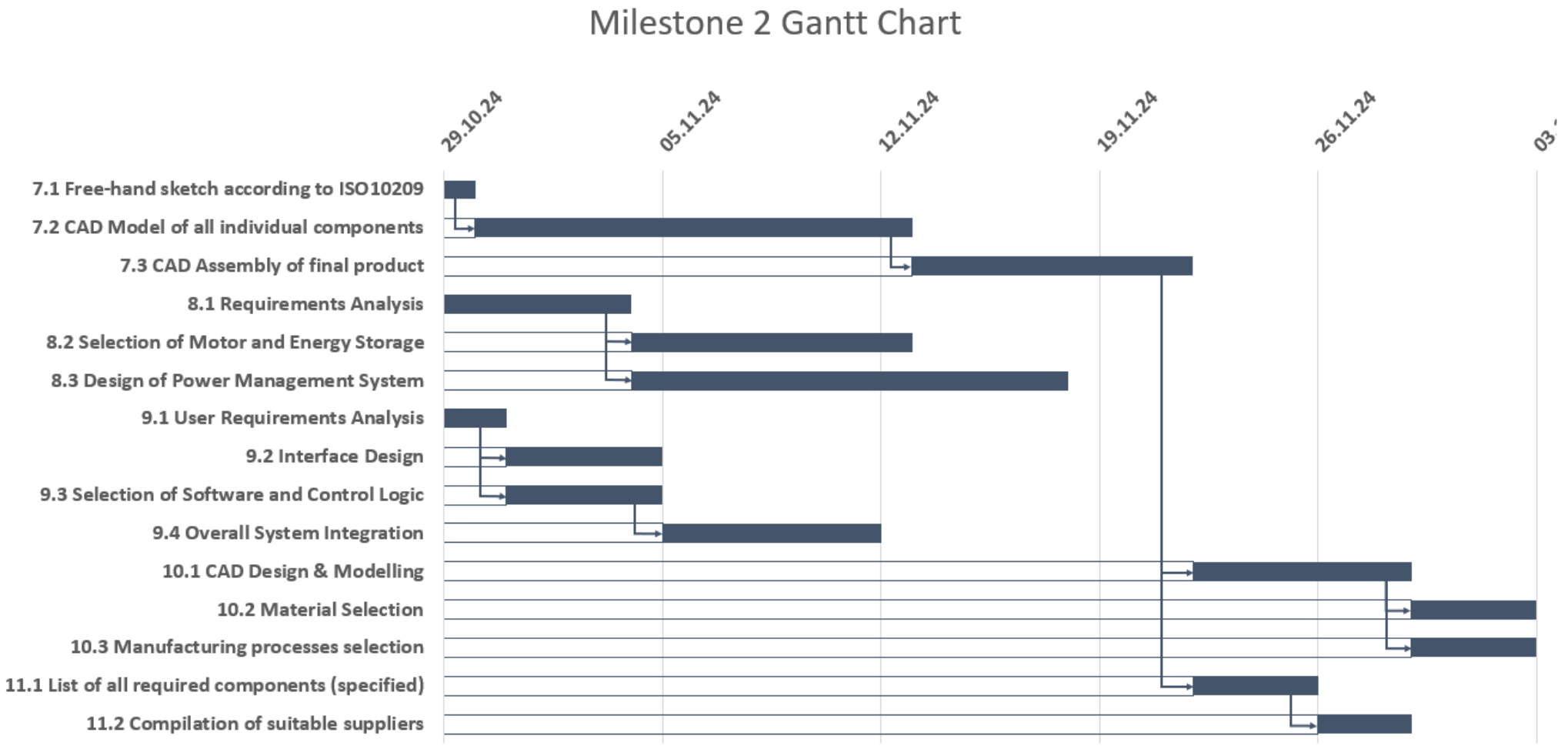


Figure 9 - Milestone 2 Gantt Chart

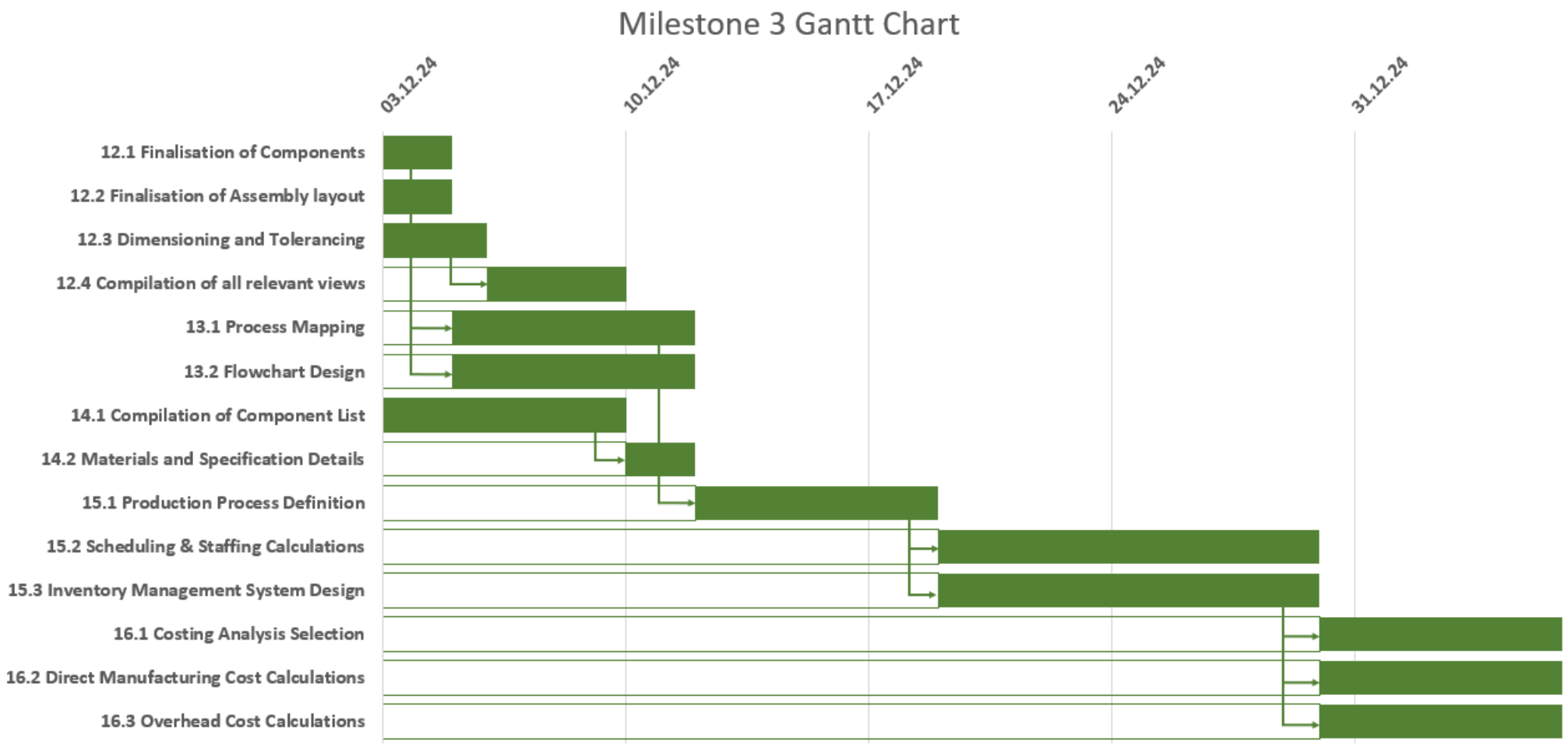


Figure 10 - Milestone 3 Gantt Chart

7 Motor and Energy Storage Dimension

1. **System Requirements for worst-case conditions**

Operational Parameters:

- **Mass of Cart**: m = 75 kg
- **Acceleration**: a = 0.347 m/s²
- **Incline Angle**: θ = 5.7°
- **Velocity**: v = 1.389 m/s
- **Wheel Radius**: r = 0.125 m
- **Coefficient of Rolling Resistance**: μ = 0.012
- **Operation Duration**: 1 hour

2. **Force Calculation(incline)**

1. **Force for Acceleration (Fa)**:

   $F_a = m \cdot a = 75\text{kg} \cdot 0.347\text{m/s}^2 = 26.03\,N$

2. **Rolling Resistance Force (Fr)**:

   $F_r = \mu \cdot m \cdot g \cdot cos(\theta)$

   Substituting:

   $F_r = 0.012 \cdot 75\text{kg} \cdot 9.81\text{m/s}^2 \cdot cos(5.7°) \approx 8.89\text{N}$

3. **Incline Resistance Force (Fi)**:

   $F_i = m \cdot g \cdot sin(\theta)$

   Substituting:

   $F_i = 75kg \cdot 9.81m/s^2 \cdot \sin(5.7°) \approx 73.21\,N$

4. **Total Force (F_{total})**:

   $F_{total} = F_a + F_r + F_i.$

   $F_{total} = 26.03N + 8.89N + 73.21N = 108.13\,N$

3. Force Calculation (flat surface)

1. **Force for Acceleration (Fa)**:

$F_a = m \cdot a = 75\text{kg} \cdot 0.347\text{m/s}^2 = 26.03\,N$

2. **Rolling Resistance Force (Fr)**:

$F_r = \mu \cdot m \cdot g$

Substituting:

$F_r = 0.012 \cdot 75\text{kg} \cdot 9.81\text{m/s}^2 \approx 8.829\text{N}$

3. **Total Force (F_{total})**:

$F_{total} = F_a + F_r$

$F_{total} = 26.03N + 8.829N = 34.859\,N$

4. Torque Calculation

1. **Torque at the Wheel (*T*)**:

$$T = F_{total} \cdot r$$

Substituting:

$$T = 108.13N \cdot 0.125m = 13.52\,Nm$$

2. **Reduction Ratio:**

$$Reduction\ ratio = \frac{T}{T_{motor}}$$

$$Reduction\ ratio = \frac{13.52Nm}{1.2Nm} = 11.3$$

3. Power Calculation

1. **Power (P)**:

$$P = F_{total} \cdot v$$

Substituting:

$$P_{required\_incline} = 108.13N \cdot 1.389m/s = 150.08W$$

$$P_{require\_flat} = 34.859N \cdot 1.389m/s = 48.42W$$

2. **Adding Safety Margin** (20%):

$$P_{require\_incline} = 150.08W \cdot 1.2 = 180.096W$$

$$P_{require\_flat} = 48.42W \cdot 1.2 = 58.104W$$

3. **Power Including Efficiency Loss:**

   The electrical power input required by the motor is:

$$P_{input} = \frac{P_{required}}{Efficiency}$$

Substituting:

$$P_{required\_incline} = 180.1W, P_{required\_flat} = 58.104 \ \ and \ Efficiency = 85\%$$

$$P_{input\_incline} = \frac{180.1W}{85\%} = 211.88W$$

$$P_{input\_flat} = \frac{58.104W}{85\%} = 68.36W$$

5. Energy Storage Requirements

1. **Energy (E)**:

$$E = P_{input\_flat} \cdot t$$

Substituting:

$$E = 68.36W \cdot 1h = 68.36\text{Wh}$$

2. **Battery Specification**:

- **Voltage**: 24 V

Capacity:

$$Capacity = \frac{E}{voltage} = \frac{68.36Wh}{24V} = 8.82Ah$$

Battery power: $I \cdot V = 30A \cdot 24V = 720W$

6. Component Selection

1. **Motor**: https://www.transmotec.de/product/B86112-24/
   - **Justification**: Meets the power and torque requirements.

2. **Motor Controller**: PWM DC Motor Speed Controller, 12 V / 24 V / 36 V / 48 V, 20 A DC Motor Driver Module, High-Performance Current Regulator : Amazon.de: DIY & Tools
    - **Justification**: Matches motor requirements for speed and torque regulation.
3. **Battery**: https://www.fruugo.de/24v-30ah-7s3p-akku-30000mah-elektrofahrrad-li-ionen-akku-pack-ladegerat/p-308656763-691099324?language=de
    - **Justification**: Provides sufficient energy for 1-hour operation with a 20% safety margin.
4. **Battery charger:** The battery is purchased with the corresponding charger as a package.

5. **Thumb Throttle: Thumb Throttle, Electric Scooter Throttle Lever with LED Display, Voltmeter Switch for E Scooter : Amazon.de: Automotive**

6. **Gear Reduction**: Can be found on page 45
    - **Ratio**: 11.3 :1
    - **Justification**: Amplifies motor torque to meet wheel torque requirements.

8 Human Machine Interface (Design of Controls)

User Input	Type	Signal type	Located	Machine Output	Type	Signal type	Located
ON/OFF	Button	Digital	Cart handle	Battery level	LED	Digital signal, Visual display	Cart handle
Velocity	Throttle	Continuous digital	Cart handle	Temperature level	LED	Digital signal, Visual display	Cart handle
Emergency stop	Button	Digital	Cart handle				

Table 8 - Human Machine Interface

There are 3 ways in which the user can communicate with the machine in our design.

- There is “ON/OFF” button. It is located on the handle of the cart, and it serves double purpose. If pressed once, it turns machine on, and if pressed again, it turns it off.
- User can control velocity of the cart via Throttle. If the throttle is not pressed, the cart can only be dragged manually and not use motorized power. Thus, the throttle also works as the “braking” system. If the throttle is pressed, velocity can be adjusted accordingly to a maximum of 5 km/h.
- If the user suddenly leaves the control loop, the throttle is no longer in use. Thus, the cart will slow down using the motor torque as braking torque as a safety measure.
- The emergency stop button can also be found on the cart handle. It is used to disrupt power immediately, in case the throttle or the ON/OFF button are not responding.

This setup of user input is designed in such a way that is only possible to run the motorized cart when in contact with it. So, the cart does not run on itself unattended risking the wellbeing of the owner, pedestrians, the loaded items, etc.

On the other hand, machine communicates with the user via LED system which can be found on cart handle: LED1; LED2; LED3.

- LED1 turns on and stays on to let the user know that the battery level is above 70%.
- This LED will then flicker when the battery level is between 25% and 70%.
- In case battery level drops under 25%, LED1 will turn off and LED2 will turn on to let the user know a recharge is recommended as soon as possible.

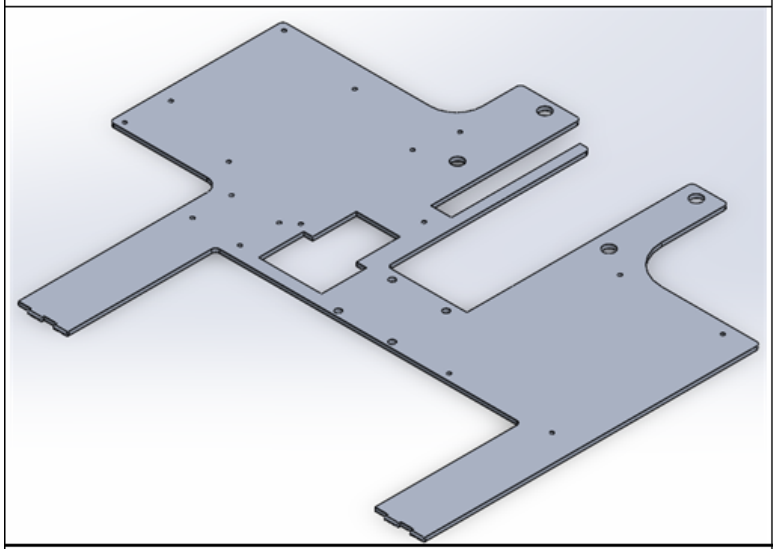
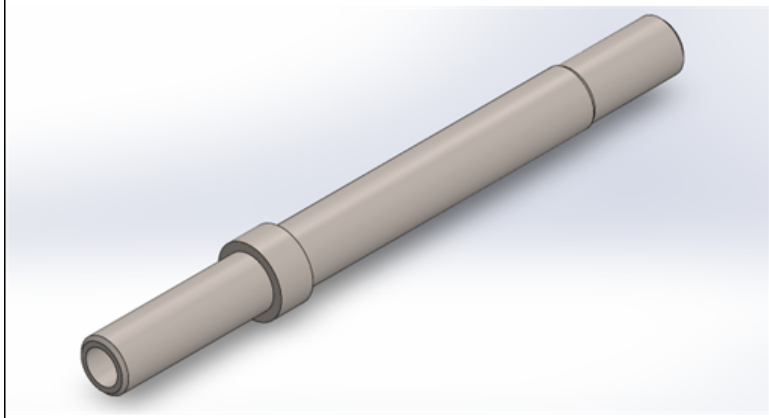
The reason why such monitor thresholds are chosen is because the battery level is limited to very few hours of running. That means that the user should be warned immediately if the battery level has dropped under 70% in case, they plan a travel which takes longer than one hour.

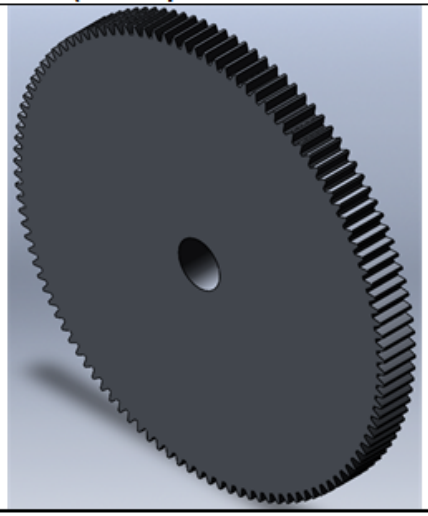
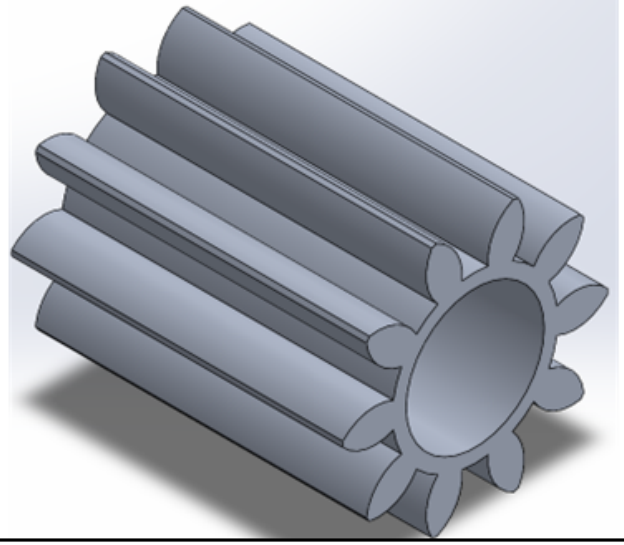
A similar temperature monitor has been designed to report to the user. Here, 2 limits are considered:

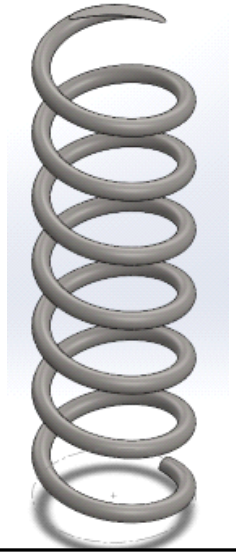
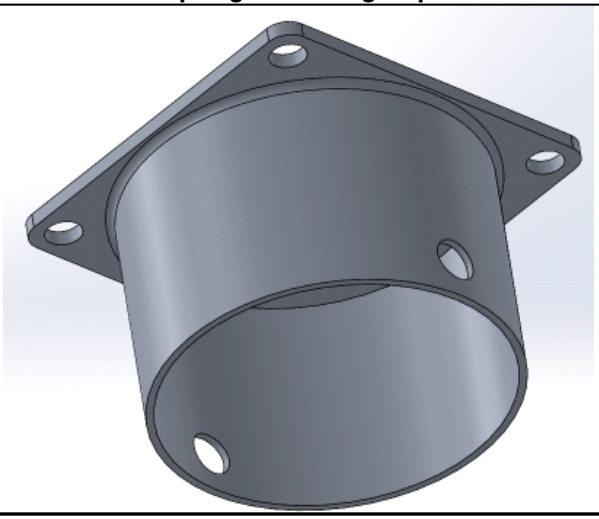
a) 60°C and 75°C for the motor,
b) 35°C and 45°C for the battery.

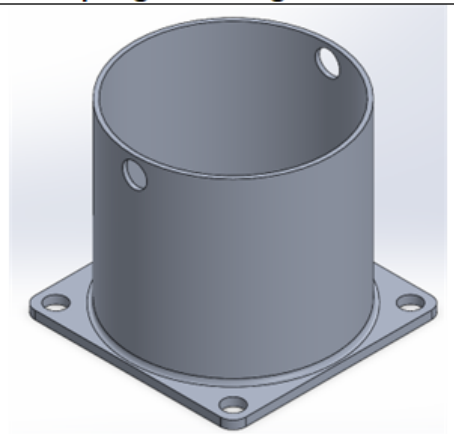
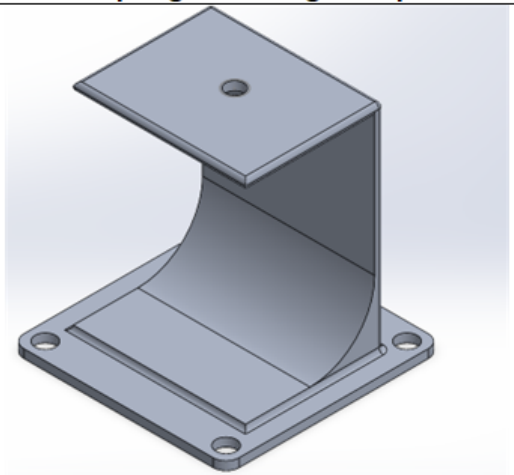
- If temperature sensors detect more than 60°C at the motor or 35°C at the battery, LED3 will turn on to let the user know and warn to take caution.
- In case temperature sensors detect 75°C at the motor or 45°C at the battery, LED3 will flicker for some seconds to alert the user that an automatic shutdown will take place.

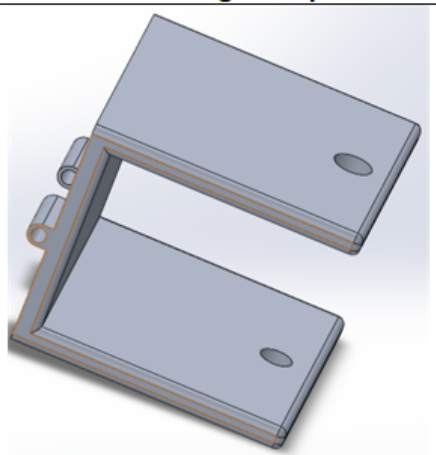
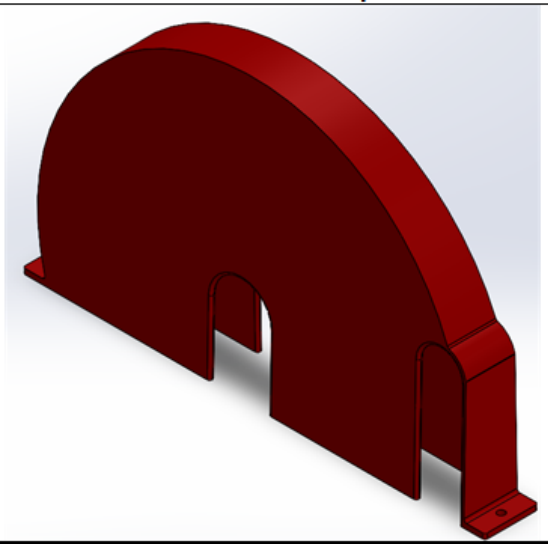
9 Technology Selection for “Make” Parts

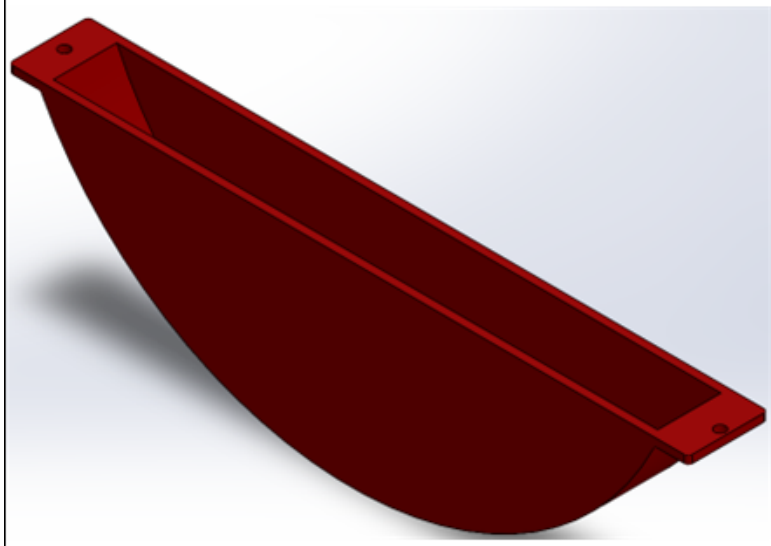
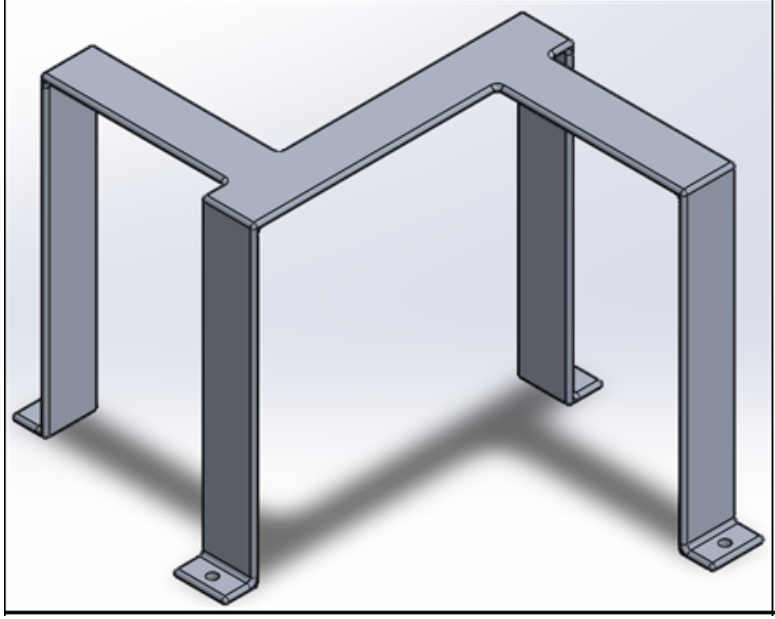
Model	Material	Manufacturing Technology
Frame 	**1060 Aluminium Alloy** **Density:** 2 700kg/m³ **Tensile Strength**: 69MPa **Elastic Modulus:** 69GPa	**Laser Cutting:** These clean cuts will create the required profile of the housing frame from the previously annealed aluminium sheet. Laser cutting will be used to remove material from the sheet and produce the frame’s outer profile. **Drilling:** Drilling all the holes that will later be used to mount other parts. **Honing:** To produce the desired tolerance for the hinge leaf holes.
Drive Shaft 	**Alloy Steel** **Density**: 7 700kg/m³ **Tensile Strength:** 724MPa **Elastic Modulus:** 210GPa	**Extrusion:** To produce the outer cylinder of the shaft with the inner hole. **CNC Turning:** Maching the outer profile of the shaft and the required surface finish and tolerances on the shaft.

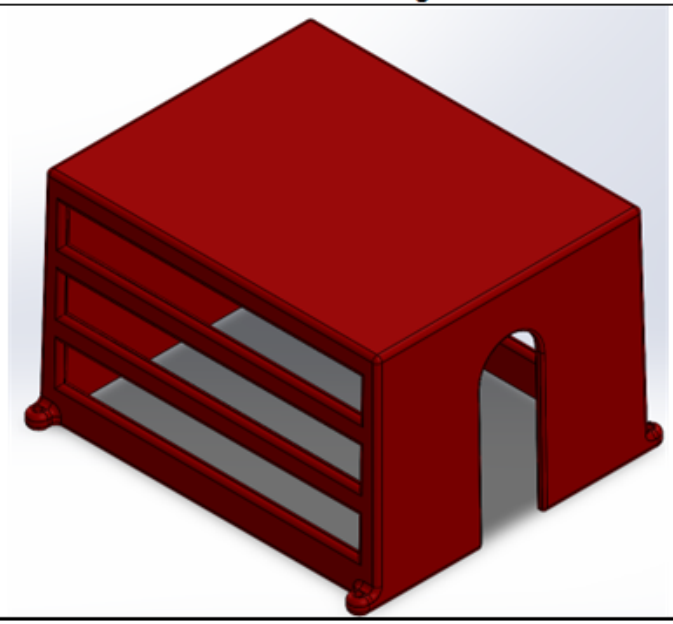
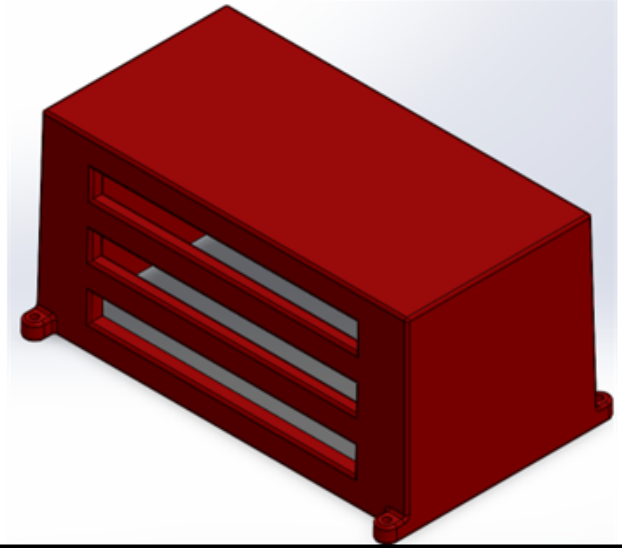
Model	Material	Manufacturing Technology
Drive Shaft Gear (DIN - Spur Gear 0.8M 113T 20PA 12FW) 	**Cast Stainless Steel** **Density:** 7 700kg/m³ **Tensile Strength:** 520MPa **Elastic Modulus:** 190GPa	**Hobbing:** Useful to produce the spur gear's teeth. **Gear Grinding:** To improve the gear tooth profile, a precision grinding process will be used, to ensure the most efficient meshing of the gear teeth. Specifically, generation grinding will be used. **Drilling:** A rotating drill bit will be used to bore a hole through the gear that allows the shaft to fit through the gear. **Honing:** A tolerance will be used on the bore of the gear to allow the required fit when the CMD is being assembled. Therefore honing is necessary to produce a polished surface finish in the bore and a tight tolerance.
Motor Gear (DIN - Spur Gear 0.8M 10T 20PA 12FW) 	**Cast Stainless Steel** **Density:** 7 700kg/m³ **Tensile Strength:** 520MPa **Elastic Modulus:** 190GPa	**Hobbing**: Useful to produce the spur gear's teeth. **Gear Grinding:** To improve the gear tooth profile, a precision grinding process will be used, to ensure the most efficient meshing of the gear teeth. Specifically, generation grinding will be used. **Drilling**: A rotating drill bit will be used to bore a hole through the gear that allows the shaft to fit through the gear. **Honing:** A tolerance will be used on the bore of the gear to allow the required fit when the CMD is being assembled. Therefore honing is necessary to produce a polished surface finish in the bore and a tight tolerance.

Model	Material	Manufacturing Technology
Spring 	**Cast Alloy Steel** **Density**: 7 300kg/m³ **Tensile Strength:** 448MPa **Elastic Modulus:** 190GPa	**CNC coiling:** The 5mm thick wire will be coiled by a cnc coiling machine to produce the required spring length, number of revolutions, and spring diameter. **Annealing:** Similar to the frame, this heat treatment process will be used to restore certain mechanical properties in the spring that would have been lost during the cold working that occurs in CNC coiling. **Grinding:** A double-end grinding technique will be used, specifically crash grinding, to produce the flat ends of the spring.
Spring Mounting Top 	**1060** Aluminium Alloy **Density:** 2 700kg/m³ **Tensile Strength**: 69MPa **Elastic Modulus:** 69GPa	**Turning:** Used to machine the cylindrical profile after first leaving some thickness in the aluminium block for the flat base profile **Drilling:** Used to drill all the holes for fastening

Model	Material	Manufacturing Technology
Spring Mounting Bottom 	**1060** Aluminium Alloy **Density:** 2 700kg/m³ **Tensile Strength**: 69MPa **Elastic Modulus:** 69GPa	**Turning:** Used to machine the cylindrical profile after first leaving some thickness in the aluminium block for the flat base profile **Drilling:** Used to drill all the holes for fastening
Spring Mounting Clamp 	**1060 Aluminium Alloy** **Density:** 2 700kg/m³ **Tensile Strength**: 69MPa **Elastic Modulus:** 69GPa	**Extrusion:** Produces from an aluminium billet the entire profile of the clamp **Brush Deburring**: To produce a smoother surface finish after extrusion **Drilling:** Used to drill the holes for fastening **Tapping:** Produces the threaded hole on the clamp

Model	Material	Manufacturing Technology
Mounting Clamp 	**1060 Aluminium Alloy** **Density:** 2 700kg/m³ **Tensile Strength**: 69MPa **Elastic Modulus:** 69GPa	**Extrusion:** Produces from an aluminium billet the entire profile of the clamp **Brush Deburring**: To produce a smoother surface finish after extrusion **Drilling:** Used to drill the holes for fastening **Honing:** For the holes on the hinge leaves to get the required tolerance **Tapping:** Produces the threaded holes on the clamp
Gear Guard Top 	**High Density Polyethylene** **Density**: 952kg/m³ **Tensile Strength:** 22.1MPa **Elastic Modulus**: 1.07 Gpa	**Injection Molding:** Producing the overall shape of the part. **Trimming & Deflashing:** Removing alll the unwanted features from the injection molded parts **Drilling:** Drilling all the holes required to fasten the part later.

Model	Material	Manufacturing Technology
Gear Guard Bottom 	**High Density Polyethylene** **Density**: 952kg/m³ **Tensile Strength:** 22.1MPa **Elastic Modulus**: 1.07 Gpa	**Injection** Molding: Producing the overall shape of the part. **Trimming & Deflashing:** Removing alll the unwanted features from the injection molded parts **Drilling:** Drilling all the holes required to fasten the part later.
Motor Bracket 	**Aluminium 5052-H32 Alloy** **Density**: 2680kg/m³ **Tensile Strength:** 230MPa **Elastic Modulus**: 70 Gpa	**Laser Cutting:** Cutting the edges of the bracket from the aluminium sheet. **Bending:** Bending the laser cut profile to produce the overall shape. **Drilling:** Drilling all the holes required to fasten the part later.

Model	Material	Manufacturing Technology
Motor Housing 	**High Density Polyethylene** **Density**: 952kg/m³ **Tensile Strength:** 22.1MPa **Elastic Modulus**: 1.07 Gpa	**Injection Molding:** Producing the overall shape of the part. **Trimming & Deflashing:** Removing alll the unwanted features from the injection molded parts **Drilling:** Drilling all the holes required to fasten the part later.
Battery Housing 	**High Density Polyethylene** **Density**: 952kg/m³ **Tensile Strength:** 22.1MPa **Elastic Modulus**: 1.07 Gpa	**Injection** Molding: Producing the overall shape of the part. **Trimming & Deflashing:** Removing alll the unwanted features from the injection molded parts **Drilling:** Drilling all the holes required to fasten the part later.

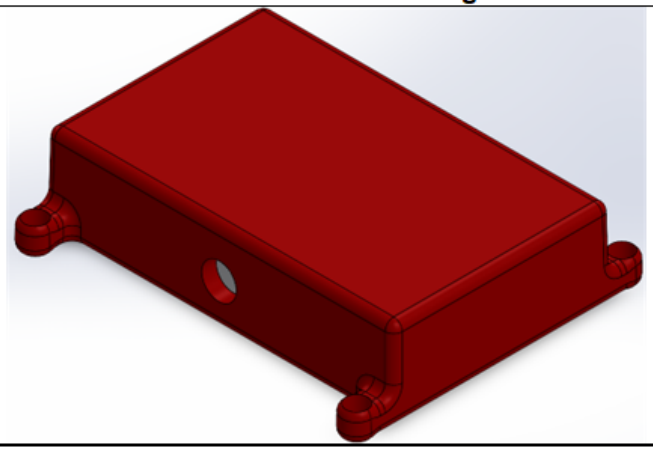
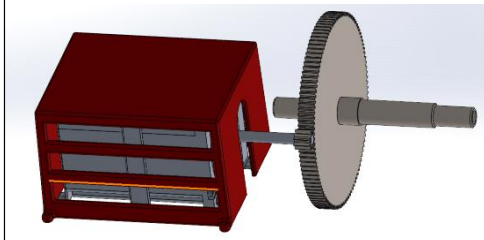
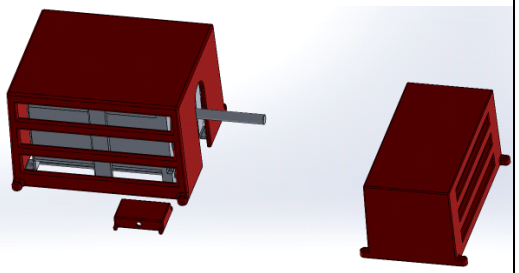
Model	Material	Manufacturing Technology
Microcontoller Housing 	**High Density Polyethylene** **Density**: 952kg/m³ **Tensile Strength:** 22.1MPa **Elastic Modulus**: 1.07 Gpa	**Injection Molding:** Producing the overall shape of the part. **Trimming & Deflashing:** Removing alll the unwanted features from the injection molded parts **Drilling:** Drilling all the holes required to fasten the part later.

Figure 11 - Manufacturing Technology for all "Make" Parts

10 Assembly Technology

Sub-Assembly	Parts Involved	Connection	Joining Technology
Wheel Asembly	Wheel Drive Shaft 2 x Bearing Bush 2 x Bearing	2 x Bearing Bush to Wheel	Pressing with interference fit
		Drive Shaft to 2 x Bearing Bush	Pressing with interference fit
		Drive Shaft to Located Bearing	Pressing with interference fit + Allen Key Lock Mechanism
		Drive Shaft to Non-Located Pillow Block Bearing	Pressing with interference fit + Allen Key Lock Mechanism
Drive System	Electric Motor Motor Housing Motor Bracket Motor Gear Drive Shaft Gear Drive Shaft	Electric Motor to Motor Housing	Clearance Fit
		Electric Motor to Motor Gear	Pressing with interference fit
		Motor Gear to Drive Shaft Gear	Gear Meshing
		Drive Shaft Gear to Drive Shaft	Pressing with interference fit
		Motor Bracket to Motor	Placement

Sub-Assembly	Parts Involved	Connection	Joining Technology
Electrical System	Battery Battery Housing Microcontroller Microcontroller Housing Electric Motor	Battery to Battery Housing	Clearance Fit with very small tolerance
		Battery to Microcontroller	Wire Connection
		Microcontroller to Microcontroller Housing	Clearance Fit with very small tolerance
		Microcontroller to Electric Motor	Wire Connection
Load Spring System	Spring Spring Mounting Bottom Spring Mounting Top Spring Mounting Clamp Hand Fastener (M5 x 10)	Spring to Spring Mounting Bottom	Clearance fit with very small tolerance + threaded fastener locking spring in spring mounting
		Spring to Spring Mounting Top	Clearance fit with very small tolerance + threaded fastener locking spring in spring mounting
		Spring Mounting Top to Spring Mounting Clamp	Threaded Fasteners
		Hand Fastener (with M5 x 10 Bolt) to Spring Mounting Clamp	Threaded Hole on mounting clamp used to fasten the bolt on the fastener

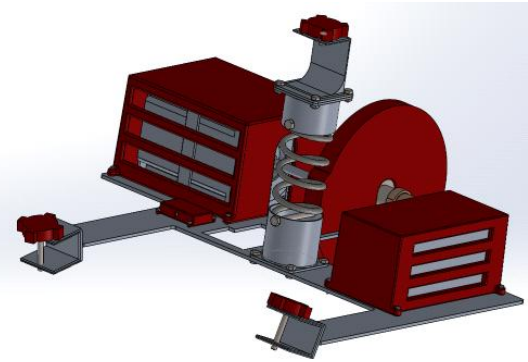
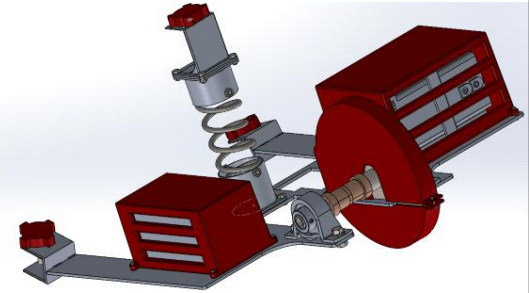
Sub-Assembly	Parts Involved	Connection	Joining Technology
Frame Assembly	Frame Motor Housing 2 x Ball Pillow Block Bearing Battery Housing Load Spring System 2 x Mounting Clamp 2 x Hinge Pin 2 x Hand Fastener (M5 x 35) Gear Guard Top Gear Guard Bottom	2 x Ball Pillow Block Bearing to Frame	Threaded Fasteners
		Motor Housing to Frame	Threaded Fasteners
		Gear Guard Top to Frame to Gear Guard Bottom	Threaded fastener connecting all three parts simultaneously
		Battery Housing to Frame	Threaded Fasteners
		Microcontroller Housing to Frame	Threaded Fasteners
		Load Spring System to Frame	Threaded Fasteners
		2 x Mounting Clamp to Frame (incl 2 x Hinge Pin)	Hinge Pin connects the hinge frames machined onto either part
		2 x Hand Fastener to 2 x Mounting Clamp	Threaded Hole on mounting clamp used to fasten the bolt on the fastener

Figure 12 - Assembly Technology for all CMD Sub-Assemblies

11 Technology Selection “Buy” Parts

Part	Qty	Technical Requirements	Origin of Requirement
Electric Motor	1	Type: Brushless DC Motor	For the required ratios of voltage to power and power to mass
		Length: < 100mm	To fit in its allocated space on the frame
		Diameter: < 70mm	To allow enough space for the nearby microcontroller
		Output Shaft Diameter: 5 - 10mm	To avoid the requirement of a large motor gear
		Power: > 150W	The minimum power required to push a fully loaded cart up an inclined slope
		Efficiency: > 80%	To maximise on the power to mass ratio of the motor
		Voltage: 24V	For a lower current during operation, therefore a lower operating temperature
		RPM: 1 766 – 2000 rpm	To provide the required angular speed of the wheel
		Start/ Stall Torque: > 0.5Nm	To avoid the requirement for a large gear reduction ratio
		Mass: < 2kg	6kg mass limit on the CMD
		IP Rating: IP54 or better	Protection of the motor from some environmental elements e.g. dust and splashes of water
		Service Life: > 500hr	Ensure the device is functional for at least 2 years
Battery	1	Type: LiFePO4	Safety, Large cycle life, thermally stable and lightweight
		Length: < 150mm	To fit in its allocated space on the frame
		Height: < 150mm	To fit in its allocated space on the frame
		Width: < 150mm	To fit in its allocated space on the frame
		Voltage: 24V	For a lower current during operation, therefore a lower operating temperature
		Amperage: > 12.5A	The minimum amperage required to produce 150W of power at the motor
		Capacity: >12.5Ah	The minimum capacity required to provide the energy required during 1hr of operation

Part	Qty	Technical Requirements	Origin of Requirement
		Mass: < 2.5kg	6kg mass limit on the CMD
		Service Life: > 2 years	Ensure the device is functional for at least 2 years
Wheel	1	Wheel Diameter: 250 - 300mm	Give the frame a height that allows easy clamping to the beach cart
		Bore Diameter: 18 - 20mm	Should match outer diameter of the bearing bush
		Section Width: 75 - 100mm	Provides enough contact area with the ground for sufficient traction during acceleration
		Tyre Material: Rubber	Widely available and lightweight
		Type of Tyre: Pneumatic Tyre	Useful on outdoor terrain including sandy beaches
		Load Capacity: > 30kg	Maximum Distributed load of cart on each wheel = 15kg
		Mass: < 250g	6kg mass limit on the CMD
Bearing Bush	2	Length: 25 - 30mm	same as cart wheel
		Inner Diameter: 16mm	Should match the Drive Shaft
		Outer Diameter: 18 - 20mm	Ideal Compromise between material robustness and reducing weight
		Flange Diameter: 23 - 25mm	To lock the bush adequately in the wheel by having enough surface contact to resist axial forces
		Flange length: 7 - 10mm	Ideal Compromise between material robustness and reducing weight
		Material: Phosphor Bronze	High wear resistance, Low Friction Properties, compatible with shafts
		Tensile Strength: > 250MPa	The required resistance to stresses on the bearing (incl a safety factor of 4)
		Mass: < 0.050kg	6kg mass limit on the CMD
Bearing	2	Type: Pillow Block Ball Bearing	Ease of Installation, alignment capabilities, durable and low maintenance
		Width: < 100mm	To fit in the allocated space next to the electric motor
		Height: 40 - 45mm	Give the frame a height that allows easy clamping to the beach cart
		Bore Diameter: 15mm	To match the drive shaft
		Operating Speed: < 4000rpm	To accommodate the maximum revolutions of the drive shaft (incl safety factor of 2)

Part	Qty	Technical Requirements	Origin of Requirement
		Housing Material: Steel with corrosion resistant plating	Durability and resistance to corrosion in outdoor environments
		Bearing Material: Ball Bearing Steel	High wear resistance and high contact fatigue strength
		Mass: < 300g	6kg mass limit on the CMD
		Corrosion Resistance: Yes	To avoid corrosion in marine environments
		Shaft Securing Mechanism: Yes	Ensuring the shaft can resist axial loads whilst also minimising weight in the drive system
		Misalignment Tolerance: Yes	Ensuring optimum performance of the drive system on rocky surfaces
		Dynamic Load Capacity: > 4kN	Eliminating the possibility of fatigue in the bearing
		Static Load Capacity: > 2kN	Eliminating deformations in the bearing that can cause failure
Bolt Type 1	4	Type of Bolt: Hex Flange Bolt	Stress distribution, ease of assembly and vibration resistance to prevent loosening
		Standard: DIN 6921	Using fasteners that are conventional and that are reliable standards in the world
		Material: AISI 1035/ 4135	High strength to density ratio and conventionality
		Coating: Yes (Galvanised)	Corrosion resistance required in some outdoor environments
		Class: 8.8	Sufficient tensile strength and hardness for all possible applications
		Thread Size: M5	Matches bore diameter on bearing housing
		Thread Type: Fine	More robust connection than coarse threads - CMD must remain rigid for optimum operation
		Bolt Length: 12 - 13mm	The length required to pass thickness of frame, bearing and nut
		Thread Length: 4.7 - 5mm	Length required to fasten with the entire thread of an M8 nut and ensure secure joining
Bolt Type 2	1	Type of Bolt: Hex Flange Bolt	Stress distribution, ease of assembly and vibration resistance to prevent loosening

Part	Qty	Technical Requirements	Origin of Requirement
		Standard: DIN 6921	Using fasteners that are conventional and that are reliable standards in the world
		Material: AISI 1035/ 4135	High strength to density ratio and conventionality
		Coating: Yes (Galvanised)	Corrosion resistance required in some outdoor environments
		Class: 8.8	Sufficient tensile strength and hardness for all possible applications
		Thread Size: M5	Providing sufficient locking in a compact size and ease of handling when fixing the CMD to the cart
		Thread Type: Fine	More robust connection than coarse threads - CMD must remain rigid for optimum operation
		Bolt Length: 10 - 11mm	Length required to adequately clamp onto the beach cart's base
		Thread Length: 10 - 11mm	Length of thread useful for securing the hand fastener during clamping to the cart
Bolt Type 3	2	Type of Bolt: Hex Flange Bolt	Stress distribution, ease of assembly and vibration resistance to prevent loosening
		Standard: DIN 6921	Using fasteners that are conventional and that are reliable standards in the world
		Material: AISI 1035/ 4135	High strength to density ratio and conventionality
		Coating: Yes (Galvanised)	Corrosion resistance required in some outdoor environments
		Class: 8.8	Sufficient tensile strength and hardness for all possible applications
		Thread Size: M5	Providing sufficient locking in a compact size and ease of handling when fixing the CMD to the cart
		Thread Type: Fine	More robust connection than coarse threads - CMD must remain rigid for optimum operation
		Bolt Length: 31 - 35mm	The length required to pass gap in mounting clamp and thickness of the nut
		Thread Length: 4.7 - 5mm	Length required to fasten with the entire thread on the mounting clamp

Part	Qty	Technical Requirements	Origin of Requirement
Bolt Type 4	12	Type of Bolt: Hex Head Screw Grade AB	Allows for higher torque application without damaging the screw head
		Standard: DIN EN 24017	Using fasteners that are conventional and that are reliable standards in the world
		Material: AISI 1035/ 4135	High strength to density ratio and conventionality
		Coating: Yes (Galvanised)	Corrosion resistance required in some outdoor environments
		Class: 8.8	Sufficient tensile strength and hardness for all possible applications
		Thread Size: M2	Providing sufficient locking in a compact size. This thread is enough to resist any vibrational motion.
		Thread Type: Fine	More robust connection than coarse threads - CMD must remain rigid for optimum operation. Also assists in vibration resistance.
		Bolt Length: 7 - 8mm	The length required to pass the thickness of the housing, frame and nut
		Thread Length: 1 - 2mm	Length required to fasten with the entire thread of the nut
Bolt Type 5	2	Type of Bolt: Hex Head Screw Grade AB	Allows for higher torque application without damaging the screw head
		Standard: DIN EN 24017	Using fasteners that are conventional and that are reliable standards in the world
		Material: AISI 1035/ 4135	High strength to density ratio and conventionality
		Coating: Yes (Galvanised)	Corrosion resistance required in some outdoor environments
		Class: 8.8	Sufficient tensile strength and hardness for all possible applications
		Thread Size: M4	Providing sufficient locking in a compact size. This thread is enough to resist the vibrational motion of the gears
		Thread Type: Fine	More robust connection than coarse threads - CMD must remain rigid for optimum operation. Also assists in vibration resistance.
		Bolt Length: 9.5 - 10mm	The length required to pass the thickness of the gear covers, frame and nut

Part	Qty	Technical Requirements	Origin of Requirement
		Thread Length: 2.5- 3mm	Length required to fasten with the entire thread of the nut
Bolt Type 6	2	Type of Bolt: Hex Head Bolt Grade AB	Offers highest ratio of bolt length to bolt diameter
		Standard: DIN EN 24014	Using fasteners that are conventional and that are reliable standards in the world
		Material: AISI 1035/ 4135	High strength to density ratio and conventionality
		Coating: Yes (Galvanised)	Corrosion resistance required in some outdoor environments
		Class: 8.8	Sufficient tensile strength and hardness for all possible applications
		Thread Size: M5	Only thread size that fits in the load spring system and provides sufficient fastening
		Thread Type: Fine	More robust connection than coarse threads. The Load Spring System must remain rigid for optimum operation. Also assists in vibration resistance.
		Bolt Length: 50 - 52mm	The length required to cover the gap in the spring mounting and lock nut
		Thread Length: 2.5- 5mm	Length required to fasten with the entire thread of the nut
Bolt Type 7	8	Type of Bolt: Hex Head Screw Grade AB	Allows for higher torque application without damaging the screw head
		Standard: DIN EN 24017	Using fasteners that are conventional and that are reliable standards in the world
		Material: AISI 1035/ 4135	High strength to density ratio and conventionality
		Coating: Yes (Galvanised)	Corrosion resistance required in some outdoor environments
		Class: 8.8	Sufficient tensile strength and hardness for all possible applications
		Thread Size: M4	Providing sufficient locking in a compact size. This thread is enough to resist the vibrational motion during operation
		Thread Type: Fine	More robust connection than coarse threads. The Load Spring System must remain rigid for optimum operation. Also assists in vibration resistance.

Part	Qty	Technical Requirements	Origin of Requirement
		Bolt Length: 7 - 8mm	The length required to cover the gap in the spring mounting and lock nut
		Thread Length: 4 - 5mm	Length required to fasten with the entire thread of the nut
Bolt Type 8	2	Type of Bolt: Hex Head Screw Grade AB	Allows for higher torque application without damaging the screw head
		Standard: DIN EN 24017	Using fasteners that are conventional and that are reliable standards in the world
		Material: AISI 1035/ 4135	High strength to density ratio and conventionality
		Coating: Yes (Galvanised)	Corrosion resistance required in some outdoor environments
		Class: 8.8	Sufficient tensile strength and hardness for all possible applications
		Thread Size: M2	Providing sufficient locking in a compact size. This thread is enough to resist any vibrational motion.
		Thread Type: Fine	More robust connection than coarse threads. The Load Spring System must remain rigid for optimum operation. Also assists in vibration resistance.
		Bolt Length: 6 - 7mm	The length required to secure the motor housing stopper without disrupting the motor's operation
		Thread Length: 6 - 7mm	Length required to fasten with the entire thread in the motor housing
Bolt Type 9	1	Type of Bolt: Hex Head Screw Grade AB	Allows for higher torque application without damaging the screw head
		Standard: DIN EN 24017	Using fasteners that are conventional and that are reliable standards in the world
		Material: AISI 1035/ 4135	High strength to density ratio and conventionality
		Coating: Yes (Galvanised)	Corrosion resistance required in some outdoor environments
		Class: 8.8	Sufficient tensile strength and hardness for all possible applications
		Thread Size: M4	Providing sufficient locking in a compact size. This thread is enough to resist the vibrational motion during operation

Part	Qty	Technical Requirements	Origin of Requirement
		Thread Type: Fine	More robust connection than coarse threads. The battery must remain rigid for optimum operation. Also assists in vibration resistance.
		Bolt Length: - 7 - 8mm	The length required to secure the battery housing stopper without affecting the battery
		Thread Length: 7 - 8mm	Length required to fasten with the entire thread on the battery housing
Nut Type 1	4	Type of Nut: Hex Flange Nut	Stress distribution, ease of assembly and vibration resistance to prevent loosening
		Standard: DIN 6923	Using fasteners that are conventional and reliable standards in the world
		Material: AISI 1035/ 4135	High strength to density ratio and conventionality
		Coating: Yes (Galvanised)	Corrosion resistance required in some outdoor environments
		Class: 8.8	Sufficient tensile strength and hardness for all possible applications
		Thread Size: M5	Matches bore diameter on bearing housing
		Thread Type: Fine	More robust connection than coarse threads - CMD must remain rigid for optimum operation
		Thread Length: 4.7 - 5mm	Ensure rigid connection of the bearing to the frame
Nut Type 2	12	Type of Nut: Chamfered Hex Thin Nut Style 0 Grade AB	Space saving and useful for resisting vibration
		Standard: ISO 4035	Using fasteners that are conventional and reliable standards in the world
		Material: AISI 1035/ 4135	High strength to density ratio and conventionality
		Coating: Yes (Galvanised)	Corrosion resistance required in some outdoor environments
		Class: 8.8	Sufficient tensile strength and hardness for all possible applications
		Thread Size: M2	Matches bolt diameter on all housings
		Thread Type: Fine	More robust connection than coarse threads - CMD must remain rigid for optimum operation. Also assists in vibration resistance.

Part	Qty	Technical Requirements	Origin of Requirement
		Thread Length: 1 - 1.5mm	Ensure rigid connection of the housings to the frame
Nut Type 3	2	Type of Nut: Chamfered Hex Thin Nut Style 0 Grade AB	Space saving and useful for resisting vibration
		Standard: ISO 4035	Using fasteners that are conventional and reliable standards in the world
		Material: AISI 1035/ 4135	High strength to density ratio and conventionality
		Coating: Yes (Galvanised)	Corrosion resistance required in some outdoor environments
		Class: 8.8	Sufficient tensile strength and hardness for all possible applications
		Thread Size: M4	Matches bolt diameter on gear guards
		Thread Type: Fine	More robust connection than coarse threads - CMD must remain rigid for optimum operation. Also assists in vibration resistance.
		Thread Length: 2 - 2.5mm	Ensure rigid sealing of both gears
Nut Type 4	2	Type of Nut: Chamfered Hex Thin Nut Style 0 Grade AB	Space saving and useful for resisting vibration
		Standard: ISO 4035	Using fasteners that are conventional and reliable standards in the world
		Material: AISI 1035/ 4135	High strength to density ratio and conventionality
		Coating: Yes (Galvanised)	Corrosion resistance required in some outdoor environments
		Class: 8.8	Sufficient tensile strength and hardness for all possible applications
		Thread Size: M5	Matches bolt diameter in load spring system
		Thread Type: Fine	More robust connection than coarse threads - Spring remains rigidly fixed in the load spring system
		Thread Length: 2.5- 3mm	Provides sufficient fastening
Nut Type 5	8	Type of Nut: Chamfered Hex Thin Nut Style 0 Grade AB	Ease of assembly and vibration resistance to prevent loosening
		Standard: ISO 4032	Using fasteners that are conventional and reliable standards in the world
		Material: AISI 1035/ 4135	High strength to density ratio and conventionality
		Coating: Yes (Galvanised)	Corrosion resistance required in some outdoor environments

Part	Qty	Technical Requirements	Origin of Requirement
		Class: 8.8	Sufficient tensile strength and hardness for all possible applications
		Thread Size: M4	Matches bore diameter of spring mounting bolts
		Thread Type: Fine	More robust connection than coarse threads - load spring system must remain rigid for optimum operation
		Thread Length: 3 - 4mm	Ensure rigid joining of the spring mounting to the frame
Motor Controller	1	Voltage Input: 24V	Matches the voltage of the motor and battery for seamless operation.
		Current Output: ≥10A	Supports motor current demands under peak load conditions.
		Control Method: PWM	Enables precise speed regulation for smooth operation and efficiency.
Thumb Throttle	1	Type: Hall Effect Sensor	Provides precise and reliable speed control by translating user input into voltage changes.
		Resolution: ≥256 levels	Ensures smooth and gradual acceleration with fine control over speed.
		Voltage Output: 0–5V	Compatible with the motor controller input for seamless integration.
		Durability: ≥50,000 cycles	Ensures the throttle lasts for the product's lifetime under frequent use.
Emergency Stop Button	1	Type: Normally Closed (NC)	Ensures the circuit is active and will immediately cut power when pressed.
		Voltage Rating: ≥ 24V	Matches the system's voltage for compatibility.
		Design: Large Mushroom Head	Ergonomic design allows quick and easy activation during emergencies.
		Durability: ≥100,000 cycles	Ensures reliable operation over the lifetime of the device.
Temperature Sensor	1	Range: -10°C to 80°C	Covers the expected operating temperatures for the motor and battery under all conditions.
		Accuracy: ±1°C	Ensures precise monitoring to detect potential overheating issues.
		Output: Digital or Analog	Provides compatibility with the microcontroller for temperature data processing.

Part	Qty	Technical Requirements	Origin of Requirement
		Response Time: ≤2 seconds	Quickly detects sudden temperature changes, enabling prompt system adjustments.
		Durability: Resistant to Vibration and Heat	Ensures reliable operation even in harsh environmental conditions, such as near the motor.
LED Indicators	3	Type: RGB or Single-Color	Provides clear and customizable status indications for system operation.
		Voltage: 3–5V	Matches the output voltage of the DC-DC converter.
		Brightness: ≥200 lumens	Ensures visibility in both indoor and outdoor conditions.
		Durability: ≥10,000 hours	Long-lasting light source to minimize replacement needs.
DC-DC Converter	1	Input Voltage: 24V	Matches the system's power source (battery).
		Output Voltage: 5V	Supplies low-voltage components like the microcontroller and LEDs.
		Output Current: ≥3A	Supports all low voltage loads simultaneously.
		Efficiency: ≥90%	Reduces energy loss and improves battery runtime.
Speed Sensor	1	RPM Range: 0–200	Matches the expected wheel rotation speeds for monitoring.
		Resolution: 1 RPM	Ensures precise feedback for the PID controller to adjust motor speed.
		Output: Analog Voltage	Compatible with the microcontroller for data processing.
		Durability: Resistant to Outdoor Conditions	Operates reliably under various environmental conditions.
Microcontroller	1	Voltage: 3.3V/5V	Compatible with the DC-DC converter output and sensor inputs.
		Digital I/O Pins: ≥10	Supports the required number of connected components (sensors, LEDs, motor controller).
		PWM Outputs: ≥2	Enables speed control for the motor via the motor controller.
		ADC Resolution: 10-bit or more	Processes precise analogue signals from sensors like throttle and battery monitor.
Fuse	1	Voltage Rating: ≥ 24V	Matches the voltage of the motor and other components to protect against overvoltage.

Part	Qty	Technical Requirements	Origin of Requirement
		Current Rating: ≥15A	Supports the system's peak current without prematurely blowing, while protecting from overcurrent.
		Type: Blade fuse	Easy to replace, has high durability, resistance to vibrations, and suitability for outdoor/mobile environments.
Relay Switch (On/Off)	1	Coil Voltage: 24V	Matches the system's operating voltage for compatibility with the motor and battery.
		Contact Rating: ≥15A	Handles the motor's peak current with a margin for safety.
		Type: SPST (Single Pole Single Throw)	Suitable for simple on/off functionality.
		Durability: ≥100,000 cycles	Ensures reliability for repeated usage over the device's lifespan.
		Response Time: ≤10ms	Provides rapid switching to avoid delays during power activation.
Relay Switch (Emergency Stop)	1	Coil Voltage: 24V	Matches the system's voltage for compatibility.
		Contact Rating: ≥15A	Accommodates peak currents during emergency stops, ensuring robust circuit breaking.
		Type: SPDT (Single Pole Double Throw)	Ensures safe circuit disconnection and fault isolation.
		Durability: ≥100,000 cycles	Reliable for frequent use in emergency situations.
		Response Time: ≤10ms	Ensures immediate system response in critical scenarios.

Table 9 - Technology Selection for all the CMD "Buy" Parts

12 Circuit Diagram

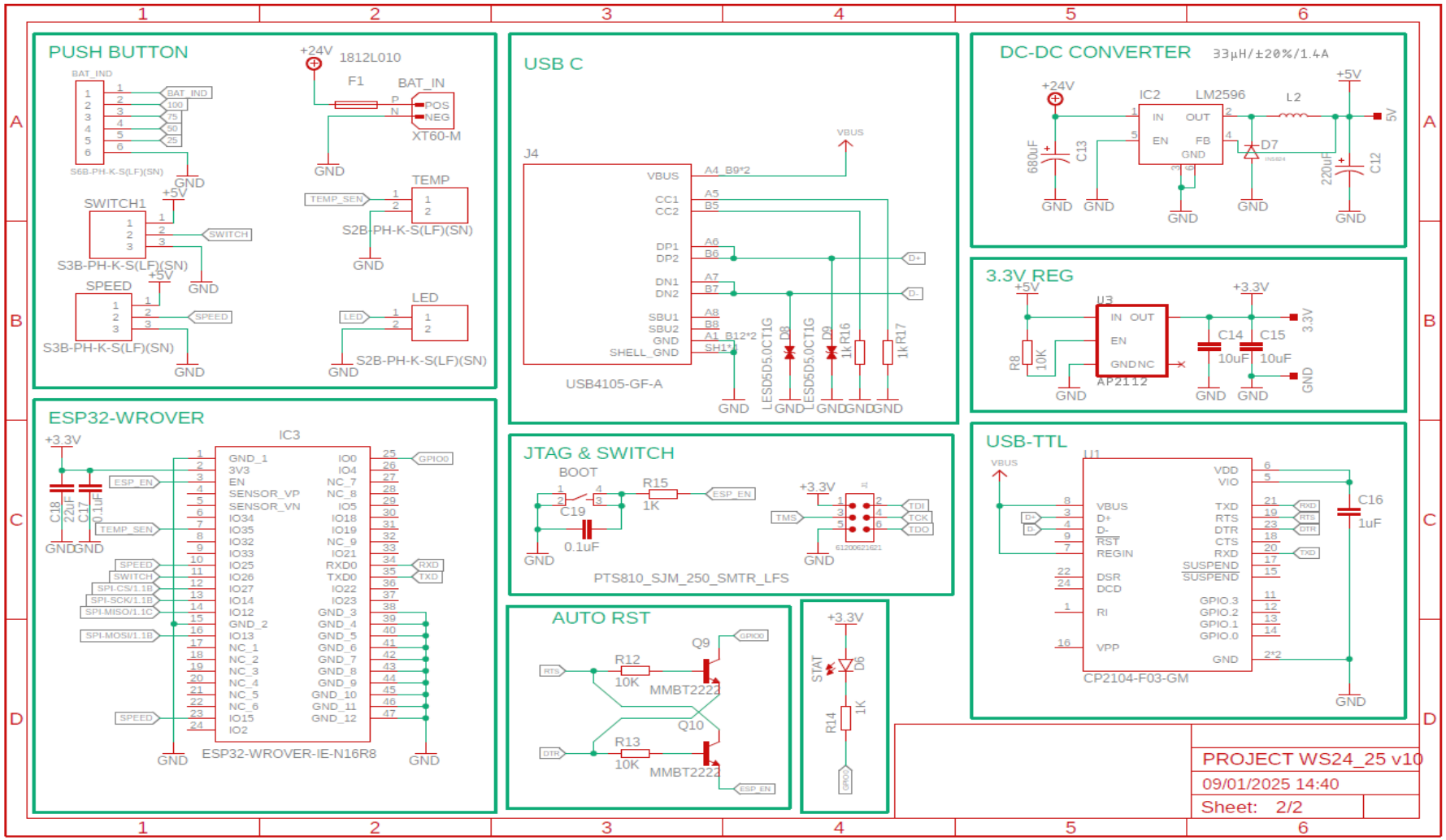


Figure 13 - Circuit diagram for the CMD

13 Program Flow Chart

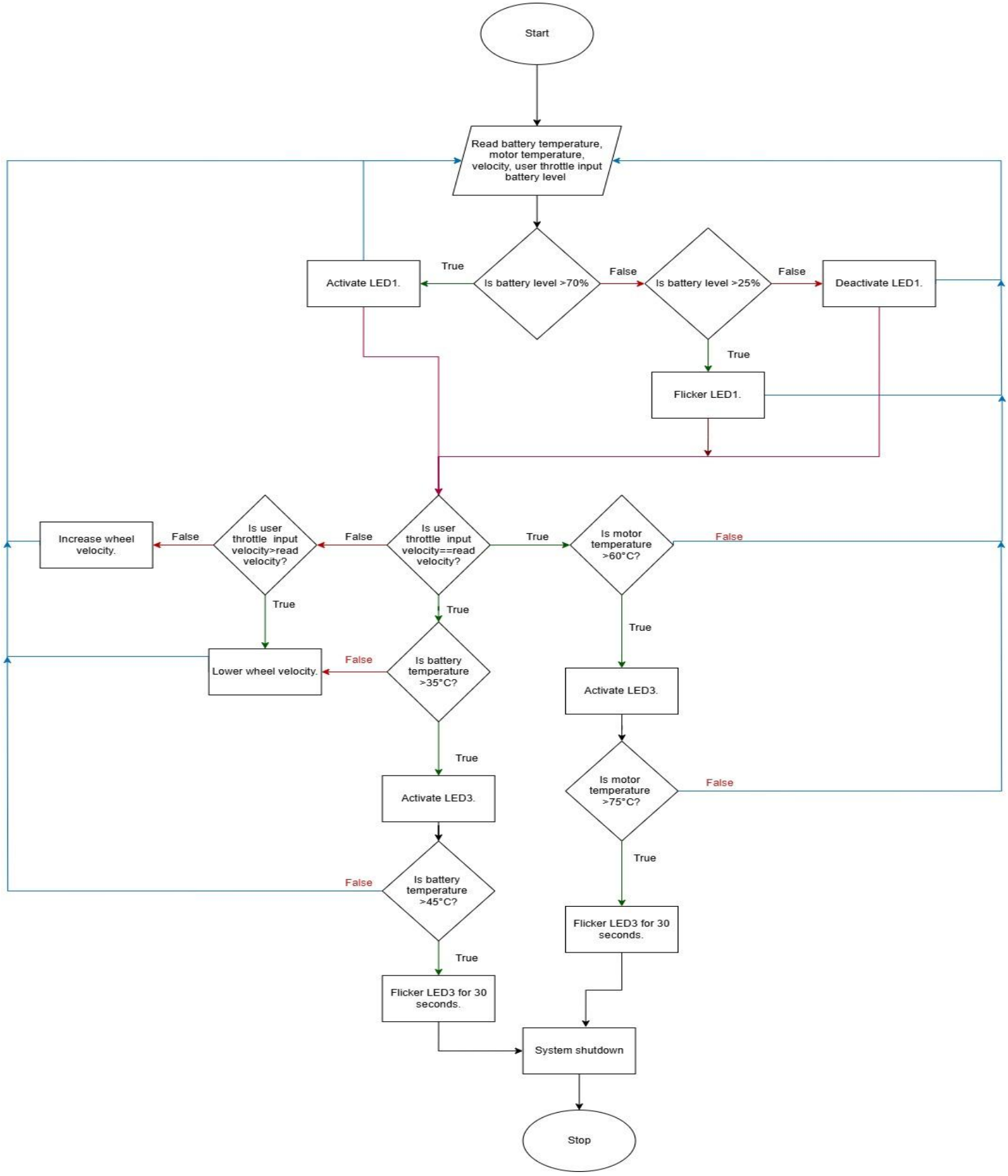


Figure 14 - Program flow chart for the CMD

As soon as the microcontroller is activated, it will read data from the battery monitor system. Depending on the charge level, it will command the corresponding LED to give information to the user.

After getting the battery data, the microcontroller will check the throttle input data and compare it to the wheel output. If the input velocity is higher than the output, it will command the wheel to reduce velocity. Same for the other way round. (This configuration also ensures that the cart doesn’t run/ stops running if there is no input from user. Thus, serves as safety measure for users, pedestrians, the loaded items, etc.

After handling the battery and wheel velocity, the microcontroller will go through the data received from the temperature sensors. If temperature sensors detect more than 60°C at the motor or 35°C at the battery, the microcontroller will command LED3 to turn on and let the user know so they can take caution.

As long as the device keeps running under the above-mentioned conditions (with certain tolerances considered such as: disturbances, feedback signal error, etc.) the microcontroller will be running in a loop keeping track of the data.

If the microcontroller receives data from the temperature sensors that the battery temperature has gone beyond 45°C or motor beyond 75°C, it will command the device to shut down in 30 seconds and alert the user.

14 Bill of Materials

14.1 Mechanical Components

ITEM	QTY.	DESCRIPTION	SPECIFICATION	DRAWING NO.	REV.	MATERIAL
1	1	Frame (Platform)				1060 Alloy
2	1	Battery	24V 30Ah Li-ion pack			
3	1	Battery Housing				PE High Density
4	1	Motor Transmotec B86112	DC, 24V, 20A, 400W			
5	1	Motor Bracket				5052-H32
6	1	Motor Housing				PE High Density
7	2	Bearing	Pillow Block Bearing 15mm diameter			1060 Alloy
8	2	Bearing Bush	16mm diameter			Phosphor Bronze 10% D, UNS C52400
9	2	Clamp				1060 Alloy
10	1	Drive Shaft				Alloy Steel
11	3	Hand Fastener				PE High Density
12	2	Hinge Pin				1060 Alloy
13	2	Spring Mounting				1060 Alloy
14	1	Spring	5mm wire diameter			Cast Alloy Steel
15	1	Rim	150mm diameter, 40mm width			1060 Alloy
16	1	Tyre	250mm diameter, 50mm maximum width			NEOPRENE
17	1	Microcontroller Housing				PE High Density
18	1	Spur Gear (Big)	DIN - Spur gear 1.25M 113T 20PA 12FW --- S113A75H50L16N			1060 Alloy
19	1	Spur Gear (Small)	DIN - Spur gear 1.25M 10T 20PA 12FW --- S10A75H50L8N			1060 Alloy
20	2	hex screw gradec_din	DIN EN 24018 - M5 x 50-WN			Alloy Steel
21	8	hex screw gradeab_din	DIN EN 24017 - M2 x 8-N			Alloy Steel
22	2	hex thin nut chamfered gradeab_din	Hexagon Thin Nut ISO 4035 - M5 - N			Alloy Steel
23	18	hex nut style 1 gradeab_din	Hexagon Nut ISO 4032 - M2 - D - N			Alloy Steel
24	4	hex flange bolt_din	DIN 6921 - M6 x 12 x 12-N			Alloy Steel
25	8	hex screw gradeab_din	DIN EN 24017 - M2 x 12-N			Alloy Steel
26	4	hex flange nut_din	Hexagon Flange Nut DIN 6923 - M6 - N			Alloy Steel
27	8	hex screw gradeab_din	DIN EN 24017 - M4 x 8-N			Alloy Steel
28	2	hex screw gradeab_din	DIN EN 24014 - M5 x 35 x 16-N			Alloy Steel

ITEM	QTY.	DESCRIPTION	SPECIFICATION	DRAWING NO.	REV.	MATERIAL
29	1	hex screw gradeab_din	DIN EN 24017 - M5 x 10-N			Alloy Steel
30	1	Gear Guard (Bottom)				PE High Density
31	1	Gear Guard (Top)				PE High Density
32	2	hex screw gradeab_din	DIN EN 24017 - M2 x 10-N			Alloy Steel
33	8	hex thin nut chamfered gradeab_din	Hexagon Thin Nut ISO 4035 - M4 - N			Alloy Steel
34	1	Spring Mounting Clamp				1060 Alloy

Table 10 - Bill of Materials for the mechanical components

14.2 Electrical Components

Component	Qty	Specs	Function	Justification	Price/unit (€)	Link
Motor	1	24V, 400W, 3200 RPM	Drives the wheel for propulsion	Chosen for high power and efficiency, suitable for 24V system	160	Brushless DC Motor - Transmotec
Battery	1	24V, 30Ah, Li-ion, 7S3P	Primary power source for the system	Provides sufficient capacity for extended runtime	84	24V 30Ah 7S3P Battery 30000mAh Electric Bike Li-ion Battery Pack & Charger | Fruugo EN
Thumb Throttle	1	0–5V with LED display	User speed input with real-time voltage display	Allows user to control speed precisely and monitor battery health	14	Thumb Throttle, Electric Scooter Throttle Lever with LED Display, Voltmeter Switch for E Scooter : Amazon.de: Automotive
Voltage Regulator (LM2596)	1	24V to 5V, 3A, TO263-5	Steps down 24V to 5V for low-power components	Regulates power for microcontroller and peripherals	3	LM2596S-ADJ/NOPB Texas Instruments | Mouser Germany

Voltage Regulator (AP2112)	1	3.3V, SOT23-5	Provides 3.3V for logic circuits	Ensures stable logic-level voltage for microcontroller	0.083	AP2112K-3.3TRG1 Diodes Incorporated | Mouser Europe
Fuse	1	20A Fast-blow	Protects against overcurrent	Prevents damage during overcurrent scenarios	1.55	SF-3812FG2000T-2 Bourns | Mouser Europe
TVS Diodes	3	SMB, Reverse Voltage Protection	Protects against voltage spikes	Protects sensitive components from power surges	0.086	SMBJ20CA-13-F Diodes Incorporated | Circuit Protection | DigiKey
Schottky Diodes	3	Reverse Polarity Protection	Prevents reverse polarity damage	Ensures safe operation in case of wiring errors	0.078	Buy Diotec Schottky Diode SKL14 SOD-123FL 40 V
BDC Motor controller	1	24V, 400w,20A with PWM	Controls motor speed and direction	Optimized for precise motor control with advanced features	13	PWM DC Electric Speed Controller 400W 6 to 60V Brushless Motor Controller with Hall Sensor for PLC Analog Control, PWM Control: Amazon.co.uk: Business, Industry & Science
Motor Driver (TMC2160A)	1	High-power stepper motor driver	Controls motor speed and direction	Optimized for precise motor control with advanced features	3.3	TMC2160A-TA Analog Devices Inc./Maxim Integrated | Integrated Circuits (ICs) | DigiKey
Power MOSFETs (IRLR024N)	8	TO252-3, Motor phase control	Handles high-current motor control	Handles motor currents efficiently and reliably	0.203	IRLR024NTRPBF Infineon Technologies | Mouser Europe
Signal MOSFETs (DMN6040SVTQ)	3	Signal Switching	Switching low-power signals	Enables low-power switching for signals	0.197	DMN6040SVTQ-7 Diodes Incorporated | Mouser Europe

Microcontroller (ESP32-WROVER)	1	Dual-core, Wi-Fi, Bluetooth, 16MB Flash	Central control of all inputs and outputs	Chosen for built-in connectivity and processing power	6	ESP32 ESP-WROOM 32.38 Pin Development Board, ESP-32S Microcontroller Processor Integrated 2-in-1 Microcontroller with CP2102 Chip WiFi NodeMCU-32S Module Pack of 2: Amazon.de: Business, Industry & Science
USB Interface (CP2104)	1	USB-to-UART, QFN	Provides USB interface for programming/debugging	Simplifies programming and debugging via USB	2.4	CP2104-F03-GM Silicon Labs | Integrated Circuits (ICs) | DigiKey
USB Connector (Type-C)	1	USB4105-GF-A	Connects USB peripherals	Ensures reliable USB connections	0.521	UJ20-C-H-G-1-SMT-TR Same Sky | Mouser Germany
JST Connectors	4	For LED/Temp/Speed/Battery connections	Connects sensors and peripherals	Provides modularity and ease of assembly	2.80	SM04B1-CPTK-1A-TB JST Automotive | Mouser Germany
Capacitors	Various	680uF, 220uF, bypassing	Filtering and local bypassing	Improves power stability and noise filtering	0.181	Safety Capacitors – Mouser UK
Resistors	Various	10kΩ, pull-up/down	Signal conditioning and current sensing	Maintains circuit integrity for signal lines	0.6	PWR4525W1002JE Bourns | Mouser Germany
Inductor	1	33uH, DC-DC conversion	Smooths DC-DC voltage conversion	Supports stable power conversion for sensitive components	0.65	SRR0735HA-330M Bourns | Mouser Germany

LED Indicator	1	RGB, 3-5V	Displays system status	Informs user of system status visually	Sold together withe the thumb throttle	Thumb Throttle, Electric Scooter Throttle Throttle Lever with LED Display, Voltmeter Switch for E Scooter : Amazon.de: Automotive

Table 11 - Bill of Materials for the electrical components

15 Production Planning

The production quantity for the year is based on the marketing analysis carried out in the initial section of this report. The resulting value of 7,000 units was used to determine the required tact time of the CMD's production process as shown in table 12.

QUANTITY	VALUE	UNIT
Production Period:	1	year
Working Days:	250	
Shifts per day:	1	
Working time per shift:	7.5	hr
Total required units:	7000	
Overall Equipment Effectiveness (OEE) [12]	0.8	
Required Processing Time for 1 unit (s):	771.43	sec

Table 12 - Takt Time Calculation

15.1 Manufacturing

15.1.1 Manufacturing Times

Based on the calculated takt time, all production processes are required to be within this time of 771.43sec. This means that all the parts required per unit of the CMD should be produced within 771.43sec. Table 13 below shows the processing times for all the parts required in a unit of the CMD

	Processing Time per part (s)	Required Qty per unit	Total Processing Time per CMD unit (s)
Frame	505.00	1	505.00
Drive Shaft	568.29	1	568.29
Drive Shaft Gear	1074.00	1	1074.00
Motor Gear	318.00	1	318.00
Spring	111.00	1	111.00
Spring Mounting Top	385.00	1	385.00
Spring Mounting Bottom	399.00	1	399.00
Spring Mounting Clamp	221.00	1	221.00
Motor Bracket	524.00	1	524.00
Mounting Clamp	157.29	2	314.57
Gear Guard Top	226.00	1	226.00
Gear Guard Bottom	190.00	1	190.00
Motor Housing	224.00	1	224.00
Battery Housing	333.00	1	333.00
Microcontoller Housing	95.00	1	95.00

Table 13 - Processing Times for Make Parts

The processing times above were generated by determining the relation between feasible machining rates and the characteristics of the part (geometry, material etc). Each machine process required different calculations for determining the processing time per part. These calculations are shown in Appendix 1 of this report, while the overall processing time for each process is shown below. Based on the calculations in Appendix 1 one can find the total time required by each process to produce the parts required for one unit of the CMD.

Production Station	Process	Processing time per unit	Required Workforce per Station	Total Workforce
1	Injection Molding	639	0.9	0.9
2	Drilling	492	0.7	0.7
3	CNC Turning	1157	1.5	1.5
4	Extrusion	492	0.7	0.7
	CNC Coiling	49		
5	Hobbing	1249	1.7	1.7
6	Laser Cutting	666	1	1
	Double End Grinding	62		
7	Gear Grinding	577	0.9	0.9
	Honing	60		
8	Trimming & Deflashing	255	0.7	0.7
	Bending	150		
	Tapping	54		
	Brush Deburring	61		
			TOTAL:	**8.1**

Table 14 - Processing Times for each machining process

As can be seen in Table 14, some processes are combined since they have processing times that are lower than the takt time. This grouping means that each production station will have a single individual working in that station. Furthermore, some production stations i.e. 3 and 5 require multiple stations because their processing times are more than the takt time. Therefore, the total required workforce for manufacturing is 8.1 employees.

15.1.2 Capacity Calculation

As Table 14 above shows, some processes require more than 771.43sec. As a result, certain processes require several machines to ensure the conditions of the takt time

are met. Table 15 below shows the necessary machines required for each machining process. Each machine must meet certain requirements as stipulated by the detailed calculations in Appendix 1.

Machine	Processing Time per unit (s)	Required No.	Technical Requirements				
CNC Turning Machine	1157.00	1.5	Feed Rate ≥ 0.075mm/rev	Cutting Speed ≥ 100m/min	Depth of Cut: 2 - 5mm	Chuck Diameter: Up to 100mm	Spindle Speed: ≤ 5000rpm
Hobbing Machine	1249.00	1.7	Feed Rate ≥ 0.35mm/rev	Cutting Speed ≥ 40m/min	Module Range: 0.5 - 10	Gear Diameter ≤ 250mm	CNC Control
Injection Molder	639.00	0.9	Injection Rate ≥ 700cm³/s	Clamping Force: 250 - 2000kN			
Gear Grinder	577.00	0.8	Cutting Speed ≥ 1500m/min	Feed rate: 10 - 300mm/min	Module Range: 0.5 - 10	CNC Control	
Laser Cutter	666.00	0.9	Laser Power ≥ 1500W	Cutting Speed > 4000mm/min	Thickness Capacity (Steel): Up to 10mm		
Drilling Machine	492.00	0.7	Feed Rate: 0.10 - 0.20mm/rev	Drill Diameter: 3 - 20mm	Spindle Speed: 200 - 6000rpm	Clamping Table Dimenstions: L > 450mm & W > 450mm	
Trimming & Deflashing Tools	362.00	0.5	Trimming Rate: 60 - 200parts/hr	Deflashing Rate: 150 - 400parts/hr			
Extruder	492.00	0.7	Extrusion Speed ≥ 0.83mm/s	Diameter Range. 20 - 150mm			
Press Brake	150.00	0.2	Pressing Force: 0.9 - 15kN	Die Width: ≥ 15mm	Bending Length: Up to 150mm		
Brush Deburring Tools	61.00	0.1	Deburring Speed ≥ 60m/min				
Tapping Tools	54.00	0.1	Cutting Speed ≥ 0.5m/min	Feed Rate ≥ 16mm/min	Spindle Speed: Up to 2000rpm		
Double End Grinder	62.00	0.1	MRR ≥ 720mm³/min				
CNC Coiler	49.00	0.1	Coiling Speed ≥ 10mm/s	Wire Diameter Range: 1 - 10mm			
Honing Tool	60.00	0.1	Cutting Speed ≥ 30m/min	Efficiency Factor ≥ 70%	Precision: ± 0.001mm		

Table 15 - Capacity Calculations for CMD Manufacturing

15.2 Assembly

15.2.1 Process Flow

Based on the design of the CMD, a specific assembly method was chosen for the device to ensure the most efficient and cost-effective production of the CMD. This method involves sub-assembly stations that produce necessary sub-assemblies that will be used in the final assembly stage to produce the CMD. This breaks down the assembly process into the following stages:

1. **Station 1**
   - Frame System Sub-Assembly
2. **Station 2**
   - Drive System Sub-Assembly
3. **Station 3**
   - Spring System Sub-Assembly
4. **Station 4**
   - Electrical Components Sub-Assembly
5. **Station 5**
   - Final Assembly

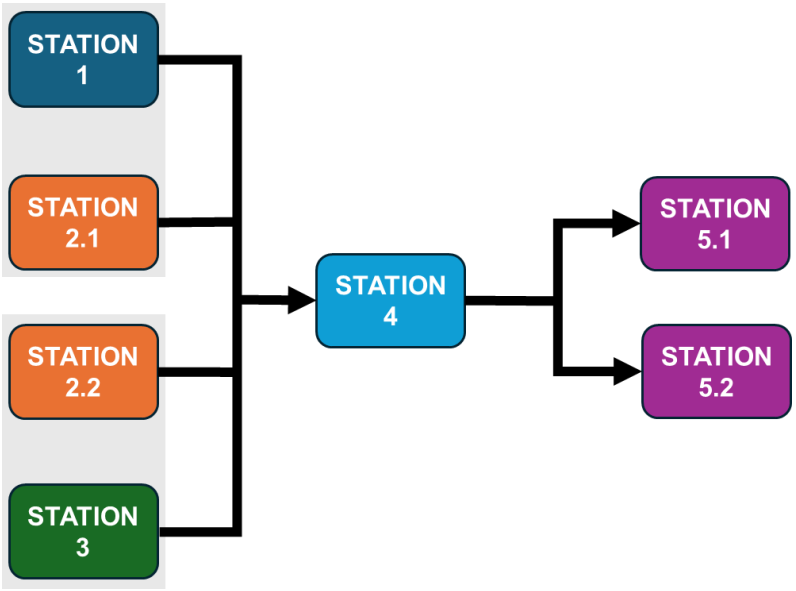


Figure 15 - Process flow between all the assembly stations

Figures 16 – 20 show the assembly time for each station of assembly.

STATION 1		
Frame System Sub-Assembly		
Process	Joining Technology	Joining Time (s)
1 x Mounting clamp to Frame	Hinge Connection	30
1 x Mounting clamp to Frame	Hinge Connection	30
1 x Hand Fastener to 1 x Mounting Clamp	Threaded Fastener	15
1 x Hand Fastener to 1 x Mounting Clamp	Threaded Fastener	15
	TOTAL:	**90**

Figure 16 - Station 1 process flow

STATION 2		
Drive System Sub-Assembly		
Process	Joining Technology	Joining Time (s)
1 x Bushing to Wheel	Press Fit	120
1 x Bushing to Wheel	Press Fit	120
Shaft to Wheel	Press Fit	180
Non-Locating Bearing to Shaft	Press Fit	180
DS Gear to Shaft	Press Fit	120
Locating Bearing to Shaft	Press Fit	180
Motor Gear to Motor Shaft	Press Fit	120
	TOTAL:	**1020**

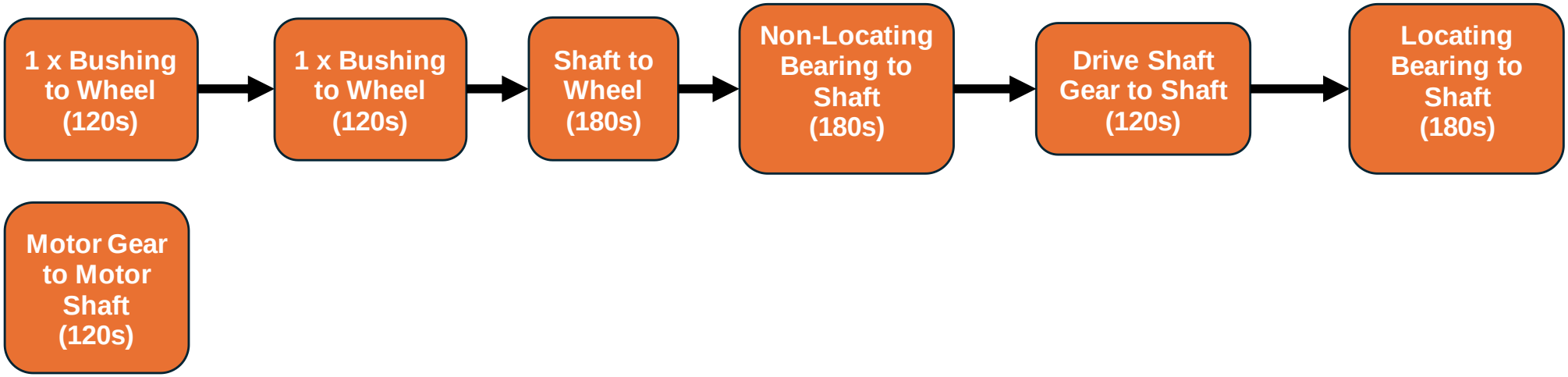


Figure 17 - Station 2 process flow

STATION 3		
Spring System Sub-Assembly		
Process	Joining Technology	Joining Time (s)
Spring to Spring Mounting Bottom	Theaded Fastener	30
Spring to Spring Mounting Top	Theaded Fastener	30
Spring Mounting Top to Spring Mounting clamp	Threaded Fasteners	90
Hand Fastener to Spring Mounting Clamp	Threaded Fastener	15
	TOTAL:	**165**

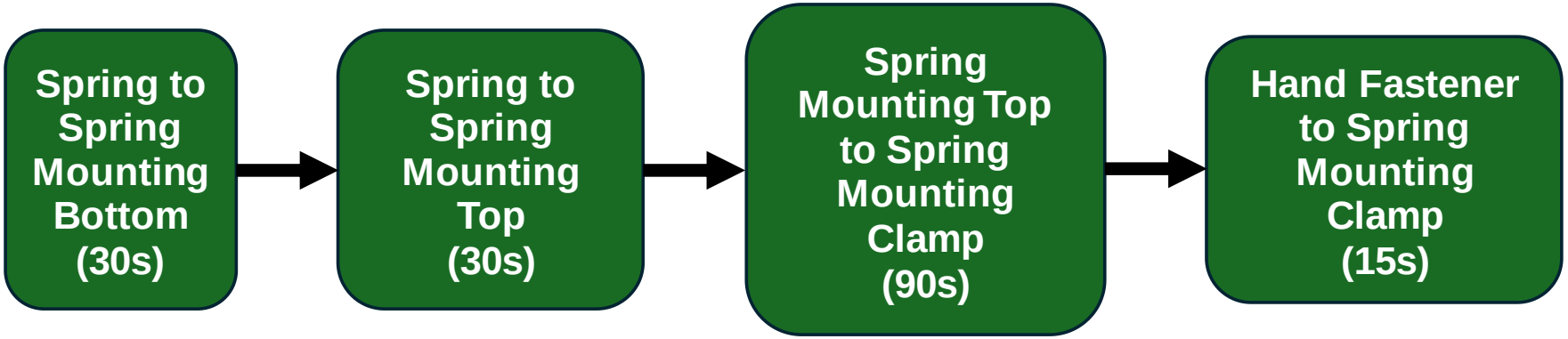


Figure 18 - Station 3 process flow

STATION 4		
Electrical Components Sub-Assembly		
Process	Joining Technology	Joining Time (s)
Battery to Fuse	Wires	15
Battery to DC-DC Converter	Wires	45
DC-DC Converter to LEDs	Wires	45
Fuse to Motor Controller	Wires	15
Motor Controller to Battery	Wires	30
Motor Controller to Motor	Wires	45
Motor Controller to Speed Sensor	Wires	45
Emergency Stop Button to Relay	Wires	30
Emergency Stop Button to Motor Controller	Wires	30
Relay to Battery	Wires	15
Relay to Motor Controller	Wires	15
Microcontroller to DC-DC	Wires	60
Microcontroller to Speed Sensor	Wires	45
Microcontroller to Temperature	Wires	45
Microcontroller to LEDs	Wires	45
Microcontroller to Motor Controller	Wires	60
Thumb Throttle to Microcontroller	Wires	60
Ground to Battery	Wires	15
	TOTAL:	**660**

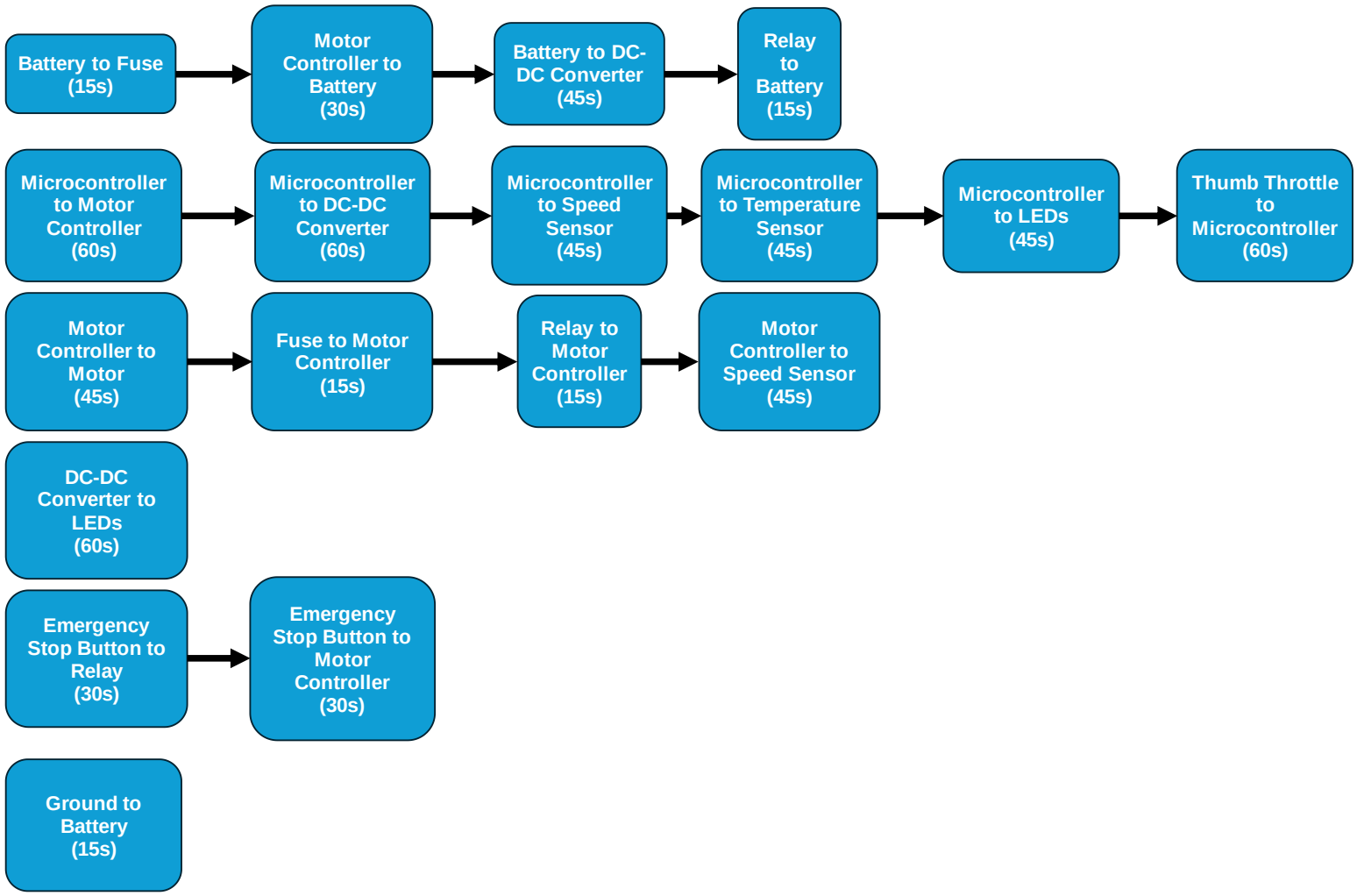


Figure 19 - Station 4 process flow

STATION 5		
Final Assembly		
Process	Joining Technology	Joining Time (s)
Non-Locating Bearing to Frame	Threaded Fasteners	120
Locating Bearing to Frame	Threaded Fasteners	120
Microcontroller to Motor	Wire Connection	150
Motor Bracket to Motor	Placement	30
Motor Gear to Drive Shaft Gear	Gear Meshing	60
Motor Bracket to Frame	Threaded Fasteners	120
Motor Housing to Frame	Threaded Fasteners	90
Gear Guards to Frame	Threaded Fasteners	90
Microcontroller to Microcontroller Housing	Placement	30
Microcontroller Housing to Frame	Threaded Fasteners	120
Battery to Battery Housing	Placement	120
Battery Housing to Frame	Threaded Fasteners	120
Spring Mounting bottom to Frame	Threaded Fasteners	60
	TOTAL:	**1230**

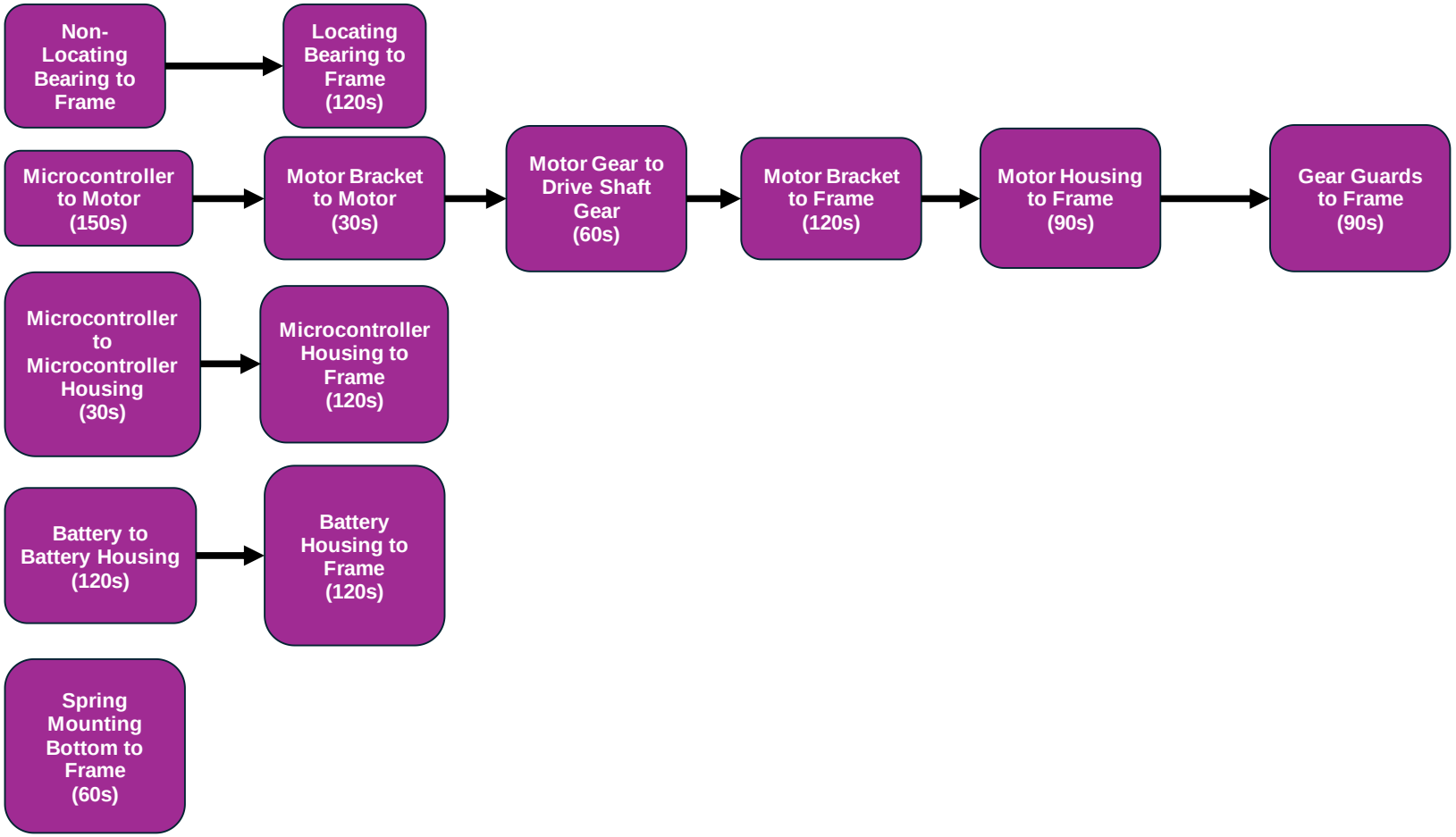


Figure 20 - Station 5 process flow

Due to varying takt times for each station, it was necessary to combine some stations as some stations required very low assembly times relative to the takt time of 771.43sec (Station 1 & 3). Furthermore, some stations (Station 2 & 4) exceed the takt time and therefore require more than 1 station to meet the necessary production capacity. Figure 21 further shows how the stations are all combined during the assembly process.

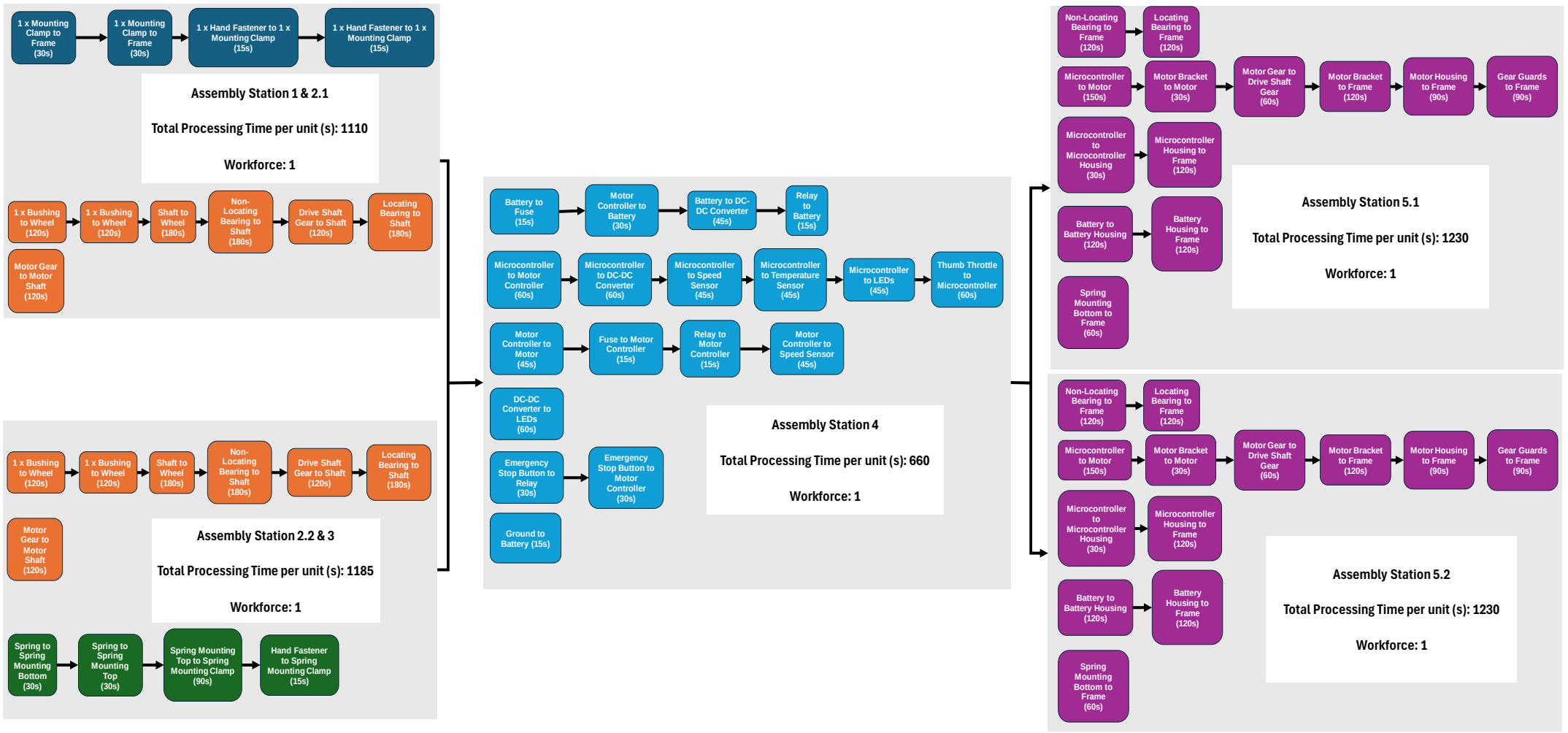


Figure 21 - Overall process flow for assembling the CMD

The joining time for each step of the process was determined using assumptions based on the following criteria:

- Joining Technology
- Part(s) Complexity
- Required Machinery or tools

For the assembly of the CMD, the only required machinery is the Hydraulic Press used in the Drive System Sub-Assembly to produce a press fit on certain parts. The requirements of the Hydraulic Press can be viewed below in Table 16. The rest of the joining steps require conventional tools such as torque wrenches and spanners.

Machine	Requirements	Processing Time (s)	Required Quantity
Hydraulic Press	Pressing Force: 5 - 30kN	1020	2

Table 16 - Hydraulic Press capacity calculation

15.2.2 Workforce

Based on the process times displayed previously, the number of required staff was determined. Table 17 shows the necessary workforce for a single year of assembling 7,000 units of the CMD.

Assembly Station	Description	Assembly time per unit (s)	Required Workforce per station	Total Worforce
1	Frame System Sub-Assembly	90	1 (Same as Assembly Station 2.1)	0.8
2.1	Drive System Sub-Assembly	1020	1 (Same as Assembly Station 1)	
2.2	Drive System Sub-Assembly	1020	1 (Same as Assembly Station 3)	0.8
3	Spring System Sub-Assembly	165	1 (Same as Assembly Station 2.2)	
4	Electrical Components Sub-Assembly	660	1	0.9
5.1	Final Assembly	1230	1	0.8
5.2	Final Assembly	1230	1	0.8
			TOTAL:	**4.1**

Table 17 - CMD assembly workforce

16 Cost Calculations

The cost calculations for the CMD were split using the following cost structure:

CMD Cost Structure		
Manufacturing	Material	Production Material
		Material Overhead
	Production	Production Wages
		Production Overhead
General Overhead	Administrative Overhead	
	Marketing and Sales Overhead	
Cost of Goods Sold		
Profit		
Cash Selling Price (6,200 units)		
Cash Discount (@ 2%)		
Target Selling Price		
Discount (@ 3%)		
Offer Price		

Table 18 - Cost Structure for the CMD

Each cost item was calculated using information from the previous section on production planning and where necessary, assumptions were used to estimate costs. For each cost item, the assumptions used are listed later in the report.

The profit estimated in Table 18 above assumes that a net profit margin of ca. 5% is reasonable for the first year of sales [13]. It should be further noted that the price per unit was determined using a sales volume of 6,200 units as highlighted in the marketing analysis. It is only in the production calculations that 7,000 units are used to plan, as buffer stock is necessary.

16.1 Material Costs

The material costs were split into 2 groups: raw materials for parts to be manufactured and manufactured parts ready for use. This is in accordance with the sections on Technology selection for make and buy parts. Furthermore, shipping costs and customs duties for these materials were included in the calculation of their cost. The list below illustrates the values used to calculate these additional costs:

- Freight Rate [14]: 100.00€ per m^3
- Customs Duty [15]: 2.50%

16.1.1 Raw Materials

Part	Material	Total Material to purchase (ton)	Total volume (m^3)	Cost per ton	Material Cost	Shipping Cost	Customs Duty	Total Cost
Frame	1060 Aluminium Alloy	7.3	2.71	2,208.00 €	16,118.40 €	271.00 €	409.74 €	16,799.14 €
Drive Shaft	Alloy Steel	1.4	0.19	1,430.00 €	2,002.00 €	19.00 €	50.53 €	2,071.53 €
Drive Shaft Gear (DIN - Spur Gear 0.8M 113T 20PA 12FW)	Cast Stainless Steel	10.5	1.37	1,776.00 €	18,648.00 €	137.00 €	469.63 €	19,254.63 €
Motor Gear (DIN - Spur Gear 0.8M 10T 20PA 12FW)	Cast Stainless Steel	0.2	0.03	1,776.00 €	355.20 €	3.00 €	8.96 €	367.16 €
Spring	Cast Alloy Steel	0.9	0.12	2,761.00 €	2,484.90 €	12.00 €	62.42 €	2,559.32 €
Spring Mounting Top	1060 Aluminium Alloy	1.6	0.6	2,208.00 €	3,532.80 €	60.00 €	89.82 €	3,682.62 €
Spring Mounting Bottom	1060 Aluminium Alloy	2.1	0.78	2,208.00 €	4,636.80 €	78.00 €	117.87 €	4,832.67 €
Spring Mounting Clamp	1060 Aluminium Alloy	0.3	0.12	1,200.00 €	360.00 €	12.00 €	9.30 €	381.30 €
Mounting Clamp	1060 Aluminium Alloy	0.6	0.23	1,200.00 €	720.00 €	23.00 €	18.58 €	761.58 €
Gear Guard Top	HDPE	0.5	0.56	1,113.60 €	556.80 €	56.00 €	15.32 €	628.12 €
Gear Guard Bottom	HDPE	0.3	0.34	1,113.60 €	334.08 €	34.00 €	9.20 €	377.28 €
Motor Housing	HDPE	1.3	1.45	1,113.60 €	1,447.68 €	145.00 €	39.82 €	1,632.50 €
Motor Bracket	Aluminium Alloy 5052-H32	3.4	0.45	2,016.00 €	6,854.40 €	45.00 €	172.49 €	7,071.89 €
Battery Housing	HDPE	1	1.12	1,113.60 €	1,113.60 €	112.00 €	30.64 €	1,256.24 €
Microcontoller Housing	HDPE	0.1	0.12	1,113.60 €	111.36 €	12.00 €	3.08 €	126.44 €
							TOTAL:	**61,802.40 €**

Table 19 - Cost of Raw Materials

16.1.2 Manufactured Parts

Part	Description	Required Production Quantity	Cost per piece	Material Cost	Shipping Cost	Customs Duty	Total Cost
Electric Motor	Brushless Motor 24VDC 20A 3200rpm 400W	7000	161.60 €	1,131,200.00 €	8,960.00 €	- €	1,356,790.40 €
Battery	24V 30Ah 7S3P Battery 30000mAh Electric Bicycle Li-ion Battery	7000	89.00 €	623,000.00 €	- €	- €	623,000.00 €
Wheel	ø250mm Pneumatic Tyre	7000	13.57 €	94,990.00 €	- €	- €	94,990.00 €
Bearing Bush	Overall Length: 28mm, Ø20mm, Ø25mm, Flange Length: 8mm	14000	9.83 €	137,620.00 €	464.80 €	- €	138,084.80 €
Bearing	Ball Pillow Block Bearings SSBPP, Stainless Steel	14000	14.21 €	198,940.00 €	1,064.00 €	- €	237,802.60 €
Bolt Type 1	Class 8.8 Hex Flange Bolt M5 x 13	28000	0.08 €	2,171.88 €	- €	- €	2,171.88 €
Bolt Type 2	Class 8.8 Hex Head Screw M2 x 8	84000	0.01 €	840.00 €	- €	- €	840.00 €
Bolt Type 3	Class 8.8 Hex Head Screw M4 x 10	14000	0.01 €	140.00 €	- €	- €	140.00 €
Bolt Type 4	Class 8.8 Hex Head Bolt M5 x 52	14000	0.09 €	1,260.00 €	- €	- €	1,260.00 €
Bolt Type 5	Class 8.8 Hex Head Screw M4 x 8	56000	0.01 €	560.00 €	- €	- €	560.00 €
Bolt Type 6	Class 8.8 Hex Head Screw M2 x 7	14000	0.01 €	140.00 €	- €	- €	140.00 €
Bolt Type 7	Class 8.8 Hex Head Screw M4 x 8	7000	0.01 €	70.00 €	- €	- €	70.00 €
Nut Type 1	Class 8.8 Hex Flange Nut M5	28000	0.02 €	560.00 €	- €	- €	560.00 €
Nut Type 2	Class 8.8 Chamfered Hex Thin Nut M2	84000	0.01 €	840.00 €	- €	- €	840.00 €
Nut Type 3	Class 8.8 Chamfered Hex Thin Nut M4	14000	0.02 €	280.00 €	- €	- €	280.00 €
Nut Type 4	Class 8.8 Chamfered Hex Thin Nut M5	14000	0.02 €	280.00 €	- €	- €	280.00 €
Nut Type 5	Class 8.8 Chamfered Hex Thin Nut M4	56000	0.02 €	1,120.00 €	- €	- €	1,120.00 €
Hand Fastener 1	M5 x 35	14000	0.74 €	10,346.00 €	- €	- €	10,346.00 €
Hand Fastener 2	M5 x 11	7000	0.66 €	4,613.00 €	- €	- €	4,613.00 €
Hinge Pin	40mm x 2mm	14000	0.35 €	4,838.40 €	175.92 €	125.36 €	5,139.68 €
Motor Controller	Voltage Input: 24V, Current Output: ≥10A, Control Method: PWM	7000	1.01 €	7,056.00 €	39.20 €	177.38 €	7,272.58 €
Thumb Throttle	Type: Hall Effect Sensor, Resolution: ≥256 levels, Voltage Output: 0–5V, Durability: ≥50,000 cycles	7000	4.99 €	34,944.00 €	59.98 €	875.10 €	35,879.08 €
Emergency Stop Button	Type: Normally Closed (NC), Voltage Rating: ≥ 24V, Design: Large Mushroom Head, Durability: ≥100,000 cycles	7000	1.06 €	7,392.00 €	39.20 €	185.78 €	7,616.98 €
Temperature Sensor	Range: -10°C to 80°C, Accuracy: ±1°C, Output: Digital or Analog, Response Time: ≤2 seconds, Durability: Resistant to Vibration and Heat	7000	4.80 €	33,600.00 €	35.00 €	840.88 €	34,475.88 €
LED Indicators	Type: RGB or Single-Color, Voltage: 3–5V, Brightness: ≥200 lumens, Durability: ≥10,000 hours	21000	0.24 €	5,040.00 €	12.60 €	126.32 €	5,178.92 €
DC-DC Converter	Input Voltage: 24V, Output Voltage: 5V, Output Current: ≥ 3A,Efficiency: ≥ 90%	7000	2.04 €	14,313.60 €	12.17 €	358.14 €	14,683.92 €
Speed Sensor	RPM Range: 0–200, Resolution: 1 RPM, Output: Analog Voltage, Durability: Resistant to Outdoor Conditions	7000	62.65 €	438,550.00 €	11.67 €	10,964.04 €	449,525.71 €
Microcontroller	Voltage: 3.3V/5V, Digital I/O Pins: ≥10, PWM Outputs: ≥2, ADC Resolution: 10-bit or more	7000	1.24 €	8,668.80 €	21.00 €	217.25 €	8,907.05 €
Fuse	Voltage Rating: ≥ 24V, Current Rating: ≥ 18A, Type: Blade fuse	7000	0.20 €	1,381.88 €	89.13 €	36.78 €	1,507.78 €
Wiring	16 - 18 AWG	12600	0.67 €	14,091.00 €	- €	- €	14,091.00 €
						TOTAL:	**3,058,167.25 €**

Table 20 - Cost of Manufactured Parts

All the source links for the items listed in the material costs can be found in Appendix 3.

16.2 Material Overhead Costs

The material overhead costs were estimated using the cost of materials above. Certain assumptions were used to estimate these overhead costs. These assumptions are listed below:

- Insurance premium on materials [16]: 0.27% of total value
- Storage and Material Handling costs [17]: 5% of total material value
- Procurement Costs [18]: 2.5% of total material value
- Depreciation of Material Handling Equipment [17]: 2% of total material value
- Wast Management cost [19]: 3% of total material value
- Other Expenses: 1.5% of total material value

Expense Item	Annual Amount
Insurance	57,427.49 €
Storage & Material Handling	155,998.48 €
Procurement Costs	77,999.24 €
Depreciation of Material Handling Equipment	31,199.70 €
Waste Management	93,599.09 €
Other Expenses (e.g. System Software, Safety Equipment, Environmental Compliance etc)	46,799.54 €
TOTAL:	**463,023.55 €**

Table 21 - Material overhead costs for the CMD

16.3 Production Labour

Based on the number of employees determined in the production planning section, the costs of production labour were determined. A salary wage was selected as the form of renumeration for these employees, meaning in addition to the gross salary of each employee, the employer is required to make additional contributions. Table 22 below illustrates all these costs.

Employee No.	Station (s)		Description	Salary	Additional Contributions								Total Cost
	Production	Assembly			Pension	Health Insurance	Long-Term Care	Unemployment Insurance	Employee Illness	Maternity Leave	Insolvency Fund	Work Accident Scheme	
Employee 1	1	-	Injection Molder	53,560.00 €	4,981.08 €	3,909.88 €	910.52 €	696.28 €	2,195.96 €	471.33 €	32.14 €	856.96 €	67,614.14 €
Employee 2	2	-	Drill Operator	53,560.00 €	4,981.08 €	3,909.88 €	910.52 €	696.28 €	2,195.96 €	471.33 €	32.14 €	856.96 €	67,614.14 €
Employee 3	3	-	CNC Machinist	53,560.00 €	4,981.08 €	3,909.88 €	910.52 €	696.28 €	2,195.96 €	471.33 €	32.14 €	856.96 €	67,614.14 €
Employee 4	3	-	CNC Machinist	53,560.00 €	4,981.08 €	3,909.88 €	910.52 €	696.28 €	2,195.96 €	471.33 €	32.14 €	856.96 €	67,614.14 €
Employee 5	4	-	Extruder & CNC Coiler	53,560.00 €	4,981.08 €	3,909.88 €	910.52 €	696.28 €	2,195.96 €	471.33 €	32.14 €	856.96 €	67,614.14 €
Employee 6	5	-	Hobbing Machine Operator	53,560.00 €	4,981.08 €	3,909.88 €	910.52 €	696.28 €	2,195.96 €	471.33 €	32.14 €	856.96 €	67,614.14 €
Employee 7	5	-	Hobbing Machine Operator	53,560.00 €	4,981.08 €	3,909.88 €	910.52 €	696.28 €	2,195.96 €	471.33 €	32.14 €	856.96 €	67,614.14 €
Employee 8	6	-	Laser Cutter & Double End Grinder	53,560.00 €	4,981.08 €	3,909.88 €	910.52 €	696.28 €	2,195.96 €	471.33 €	32.14 €	856.96 €	67,614.14 €
Employee 9	7	-	Gear Grinder & Honer	53,560.00 €	4,981.08 €	3,909.88 €	910.52 €	696.28 €	2,195.96 €	471.33 €	32.14 €	856.96 €	67,614.14 €
Employee 10	8	-	Trimmer & Deflasher, Bending Machine Operator, Tapper and Brush Deburrer	53,560.00 €	4,981.08 €	3,909.88 €	910.52 €	696.28 €	2,195.96 €	471.33 €	32.14 €	856.96 €	67,614.14 €
Employee 11	-	1 & 2.1	Hydraulic Press Operator & Sub-Assembler	53,560.00 €	4,981.08 €	3,909.88 €	910.52 €	696.28 €	2,195.96 €	471.33 €	32.14 €	856.96 €	67,614.14 €
Employee 12	-	2.2 & 3	Hydraulic Press Operator & Sub-Assembler	53,560.00 €	4,981.08 €	3,909.88 €	910.52 €	696.28 €	2,195.96 €	471.33 €	32.14 €	856.96 €	67,614.14 €
Employee 13	-	4	Electrical components Assembler	53,560.00 €	4,981.08 €	3,909.88 €	910.52 €	696.28 €	2,195.96 €	471.33 €	32.14 €	856.96 €	67,614.14 €
Employee 14	-	5.1	Final Assembler	53,560.00 €	4,981.08 €	3,909.88 €	910.52 €	696.28 €	2,195.96 €	471.33 €	32.14 €	856.96 €	67,614.14 €
Employee 15	-	5.2	Final Assembler	53,561.00 €	4,981.17 €	3,909.95 €	910.54 €	696.29 €	2,196.00 €	471.34 €	32.14 €	856.98 €	67,615.41 €
												TOTAL:	**1,014,213.42 €**

Table 22 - Production Labour costs for the CMD

Assumptions:

All production employees are at a skill level equivalent to an experienced (8+ years) machine operator. It is this skill level that has been used to estimate the gross salary of each production employee [20]. And in addition to this gross salary, certain contributions from the employer were calculated using the following percentage contributions [21]:

Type of Contribution	Contribution
Pension	9.30%
Health	7.30%
Long-Term Care	1.70%
Unemployment	1.30%
Employee Illness	4.10%
Maternity Leave	0.88%
Insolvency Fund	0.06%
Work Accident Scheme	1.60%

Table 23 - Employer Contributions for the production labour

The contributions above are typical of individuals employed in the manufacturing industry in Germany. The contribution for maternity leave was included to account for the possibility of women being employed in these roles.

16.4 Production Overhead

To better estimate the cost of production overheads, machines were selected based on the requirements highlighted in the capacity calculations. The details of these machines have been added in a table in Appendix 2. Following this selection, the list of assumptions below were used to estimate all the production overhead costs.

List of Assumptions:

- 10 Year Straight-Line Depreciation on all machinery
- Maintenance Cost range: 3 – 5% of machine's purchase cost
- Electricity Cost [22]: 0.17€ per kWh
- Indirect Labour cost: based on the salary of a relatively experienced supervisor and ad-hoc staff throughout the year.
- Facility Maintenance [23]: 15% of rent

- Rent [24]: Based on warehouse rental prices of 8.50€/m^2 on a 900m^2 warehouse.
- All other production overheads: calculated based on the already determined production overheads [25]. Percentages vary from 2 – 5%.

Expense Item		Annual Amount
Indirect Labour		100,000.00 €
Machine Depreciation		273,900.00 €
Sundries		30,000.00 €
Facility Maintenance		13,770.00 €
Equipment Maintenance		136,950.00 €
Quality Control		93,599.09 €
Safety & Compliance		30,000.00 €
Utilities	Rent	91,800.00 €
	Electricity	54,493.02 €
	Water	30,000.00 €
	Gas	30,000.00 €
	Compressed Air	20,000.00 €
	TOTAL:	**904,512.11 €**

Table 24 - Production overhead costs

16.5 General Overhead

Like previous overheads, administrative overhead was estimated based on the assumption that administrative overhead for manufacturing typically ranges from 15 – 40% of the total manufacturing cost [25]. The production of the CMD constitutes light to medium manufacturing and therefore a percentage of 15% was chosen.

Marketing and Sales overhead cost was based on the salaries of 3 employees with 4 – 5 years of experience and who travel several times a year around Europe and to the United States achieving sales [26]. In addition to this, estimates were made for marketing materials such as market reports, brochures and marketing campaigns. Table 25 illustrates all these costs while the detailed breakdown of the costs for marketing personnel is shown in Appendix 4.

Marketing Expenses	
Expense Item	**Value**
Personnel	200,153.52 €
Travel Expenses	40,000.00 €
Marketing Materials	50,000.00 €
Marketing Research	10,000.00 €
TOTAL:	**300,153.52 €**

Table 25 - Overview of Marketing and Sales overhead costs

16.6 Purchasing Discounts

All discounts are equivalent to conventional discounts used in B2B sales and are based on payment speed and order quantity [27].

16.7 CMD Offer Price

CMD Cost Structure			
Manufacturing	Material	Production Material	3,119,969.64 €
		Material Overhead	463,023.55 €
	Production	Production Wages	824,893.58 €
		Production Overhead	904,512.11 €
	TOTAL:		5,312,398.88 €
General Overhead	Administrative Overhead (15%)		796,859.83 €
	Marketing and Sales Overhead		300,153.52 €
Cost of Goods Sold:			6,409,412.23 €
Profit:			500,000.00 €
Cash Selling Price (6,200 units)			1,114.42 €
Cash Discount (@ 2%)			22.29 €
Target Selling Price:			1,136.71 €
Discount (@ 3%)			34.10 €
Offer Price:			**1,170.81 €**

Table 26 - CMD price calculation

Appendices

Appendix 1 - Processing Time, detailed calculations

Laser Cutting

$$v = k \times \frac{P}{t}$$

v (cutting speed, mm/min):	4000	4000
P (Laser Power, W):	1500	1500
t (Material Thickness, mm):		3
k (Empirical Constant for Aluminium):		8

$$T_C = \frac{L}{v}$$

T_C	Total Cutting Time (s)
L	Total Cutting Length (mm)

$$T_P = T_{PI} \times P_I$$

T_P	Total Piercing Time (s)
T_{PI}	Time per piercing (s)
P_I	Total piercings

$$T = T_C + T_P$$

Part	Quantity	Setup Time per part (s)	L (mm)	v (mm/min)	Loading (s)	T_C (s)	T_{PI} (s)	P_I	T_P (s)	T (s)	Unloading (s)	Batch Size	Processing Time per part (s)
Frame	7000	900	2248.06	4000.00	150.00	33.72	3.00	2	6.00	40.00	120.00	28.00	343.00
Motor Bracket	7000	900	1189.95	4000.00	150.00	17.85	2.00	1	2.00	20.00	120.00	28.00	323.00

CNC Turning

$$T = \frac{L}{f \times N}$$

T_T	Turning Time (min)
L	Length of Cut (mm)
N	Spindle Speed (rpm)
f	Feed Rate (mm/rev)

$$N = \frac{1000 \times V}{\pi \times D}$$

V	Cutting speed (m/min)
D	Diameter of workpiece (mm)

Part	Setup Time per part (s)	D (mm)	V (m/min)	N (rpm)	f (mm/rev)	L (mm)	Loading Time (s)	T_T (s)	Unloading Time (s)	Total Time per part (s)	Batch Size	Processing Time (s)
Drive Shaft	600	22	100	1446.86	0.075	182	150	101	150	701	28	423
Spring Mounting Top	600	47	100	677.26	0.075	32	150	38	150	638		360
Spring Mounting Bottom	600	47	100	677.26	0.075	44	150	52	150	652		374

CNC Hobbing

$$T = \frac{b + L}{f \times K \times N}$$

T_C	Cutting Time per tooth (min)
b	Gear Face Width (mm)
L	Overrun Allowance (mm)
f	Feed Rate (mm/rev)
N	Hob Speed (rpm)
K	No. of Hob Starts

$$N = \frac{1000 \times V_c}{\pi \times D}$$

Vc:	Cutting Speed (mm/min)
D:	Tool Diameter (mm)

	Module	Setup Time (s)	V_C (mm/min)	D (mm)	b (mm)	L (mm)	f (mm/rev)	N (rpm)	K	T_C (s)	No. of Teeth	Cycle Time (s)	Batch Size	Processing Time (s)
Drive Shaft Gear:	0.8	300	45	40	12	10	0.35	358.098622	2	5.26590769	113	596	28	896
Motor Gear:	0.8	300	45	40	12	10	0.35	358.098622	2	5.26590769	10	53		353

Gear Grinding

$$MRR = w \times a \times f$$

Total Volume = Stock Allowance per Side × Gear Face Width × Pitch Diameter

MRR	Material Removal Rate (mm^3/min)
w	Gear Face Width (mm)
a	Depth of Cut (mm)
f	Feed Rate (mm/min)

$$\text{Grinding Time (per pass)} = \frac{\text{Volume to Remove}}{MRR}$$

Total Grinding Time = Grinding Time (per pass) × Number of Passes

	Stock Allowance per side	w (mm)	Pitch Diameter (mm)	Total Volume (mm^3)	a (mm)	f (mm/min)	MRR (mm^3/min)	Grinding time, per pass (s)	No. of Passes	Setup time (s)	Total Grinding Time (s)	Batch Size	Cycle Time (s)	Processing Time (s)
Drive Shaft Gear:	0.2	12	90.4	216.96	0.02	169.5	40.68	320	1	1200	320	28	363	363
Motor Gear:	0.24	12	8	23.04	0.02	30	7.2	192	1	600	192		214	214

Honing

$$MRR = Area\ of\ contact \times Cutting\ Speed \times Efficiency\ Factor$$

$$Honing\ Time = \frac{Volume\ of\ Material\ to\ remove}{MRR}$$

	A (mm^2)	V_C	E	MRR	$V_{MATERIAL}$	Setup Time (s)	Honing time (s)	Batch Size	Cycle Time (s)	Quantity required per unit	Time
Frame	62.8318531	30	0.7	1319.469	13.19468915	300	1	28	12	1	12
Drive Shaft Gear	90.4778684	30	0.7	1900.035	60.69557007	300	1		12	1	12
Motor gear	90.4778684	30	0.7	1900.035	19.22654704	300	1		12	1	12
Mounting Clamp	62.8318531	30	0.7	1319.469	13.19468915	300	1		12	2	24

Drilling

$$T_D = \frac{L}{f \times N}$$

T_D	Drilling Time (min)
L	Hole Depth + Drill Tip Length (mm)
f	Feed Rate (mm/rev)
N	Spindle Speed (rpm)

$$N = \frac{1000 \times V_c}{\pi \times D}$$

V_C	Cutting Speed (m/min)
D	Drill Diameter (mm)

	f (mm/rev)	VC (m/min)	D (mm)	N (rpm)	L (mm)	T_D (s)	No. of Holes	Setup Time (s)	Cycle Time (s)	Batch Size	Cycle Time (s)	Processing Time (s)
Frame	0.12	100.00	9.00	3536.78	30.00	5.00	24.00	900.00	120.00	28	153.00	153
Drive Shaft Gear	0.15	15.00	16.00	298.42	60.00	81.00	1.00	600.00	81.00	28	103.00	103
Motor Gear	0.10	15.00	5.00	954.93	27.00	17.00	1.00	600.00	17.00	28	39.00	39
Spring Mounting Top	0.12	100.00	5.00	6366.20	18.00	2.00	4.00	450.00	8.00	28	25.00	25
Spring Mounting Bottom	0.12	100.00	5.00	6366.20	18.00	2.00	4.00	450.00	8.00	28	25.00	25
Spring Mounting Clamp	0.12	100.00	5.00	6366.20	18.00	2.00	4.00	450.00	8.00	28	25.00	25
Mounting Clamp	0.12	100.00	5.00	6366.20	18.00	2.00	4.00	450.00	8.00	56	17.00	34
Gear Guard Top	0.15	400.00	5.00	25464.79	17.00	1.00	2.00	450.00	2.00	28	19.00	19
Gear Guard Bottom	0.15	400.00	5.00	25464.79	17.00	1.00	2.00	450.00	2.00	28	19.00	19
Motor Bracket	0.15	400.00	3.00	42441.32	11.00	1.00	4.00	450.00	4.00	28	21.00	21
Motor Housing	0.10	400.00	3.00	42441.32	12.00	1.00	4.00	180.00	4.00	28	11.00	11
Battery Housing	0.10	400.00	3.00	42441.32	12.00	1.00	4.00	180.00	4.00	28	11.00	11
Microcontoller Housing	0.10	400.00	3.00	42441.32	12.00	1.00	4.00	60.00	4.00	28	7.00	7

CNC Coiling

$$T_{coil} = \frac{L_{spring}}{V_{coil}}$$

T_{COIL} (time to coil, s):	15.216
L_{SPRING} (length of spring, mm):	152.16
V_{COIL} (coiling speed of machine, mm/s):	10

$$L_{spring} = N \times P$$

N (Number of coils):	7
P (Pitch, mm):	21.74

Part	Setup Time (s)	T_{COIL} (s)	Batch Size	Cycle Time (s)	Processing Time (s)
Spring	900	16	28	49	49

Grinding

$$MRR = V_f \times D_w \times W_w$$

MRR (mm^3/min):	720
Volume to remove (mm^3):	338.06
Grinding Time (s):	28.17166667

Part	Setup Time (s)	Grinding Time (s)	Batch Size	Cycle Time (s)	Processing Time (s)
Spring	900	29	28	62	62

Extrusion

$$Q = A \times v$$

Q (Flow Rate, mm^3/s):	Flow Rate (mm^3/s)
A	Extruded Profile Cross-Section (mm^2)
v	Extrusion Speed (mm/s)

$$t = \frac{V}{Q}$$

t	Extrusion Time (s)
V	Total volume of part (mm^3)

	A (mm^2)	v (mm/s)	Q (mm^3/s)	V (mm^3)	Setup Time (s)	t (s)	Batch Size	Cycle Time (s)	Processing Time (s)
Drive Shaft	314.1592654	0.833333333	261.7993878	21026.18	1800	81	28	145.285714	146
Spring Mounting Clamp	310.9673913	0.833333333	259.1394928	14304.56	1800	56		120.285714	121
Mounting Clamp	305.68675	0.833333333	254.7389583	12031.87	1800	48		112.285714	225

Brush Deburring

$$t_D = \frac{A}{S} \times F$$

t_D	Deburring time per part (s)
A	Part Surface Area (mm^2)
F	Pass Time Factor
S	Deburring Speed (m/s)

	A (mm^2)	S (m/s)	F	t_D (s)	No. of Passes	Setup time (s)	Batch Size	Cycle Time (s)	Processing Time (s)
Spring Mounting Clamp	0.01176103	1	10	7.056618	4	300	28	29	29
Mounting Clamp	0.0086119	1	10	5.16714	3	300	56	16	32

Tapping

$$N = \frac{1000 \times V_c}{\pi \times D}$$

N (Spindle speed, rpm):	31.83098862
V_C (cutting speed, m/min):	0.5
D (Drill Diameter, mm):	5

$$f = N \times P$$

f (feed rate, mm/min):	15.9154943
P (pitch, mm):	0.5

$$T = \frac{L}{f}$$

T	Tapping time (min)
L	Depth of Thread (mm)

	L (mm)	Setup Time (s)	Batch size	T (s)	Processing Time (s)
Spring Mounting Clamp	2	300	28	8	8
Mounting Clamp	6	300	56	23	46

Bending

$$F = \frac{K \times T^2 \times L}{W}$$

F	Required force (kN)
K	Material constant for aluminium
T	Material Thickness (mm)
L	Bend Length (mm)
W	Die Opening (mm)

Bend No.	T (mm)	L (mm)	W (mm)	K	F (kN)	Setup Time (s)	Loading (s)	Bending (s)	Unloading (s)	Time per bend (s)	Batch Size	Processing Time (s)
1	2	88	15	0.35	8.21333333	600	5	6	5	16	28	150
2	2	88	15	0.35	8.21333333		5	6	5	16		
3	2	88	15	0.35	8.21333333		5	6	5	16		
4	2	88	15	0.35	8.21333333		5	6	5	16		
5	2	10	15	0.35	0.93333333		5	6	5	16		
6	2	10	15	0.35	0.93333333		5	6	5	16		
7	2	10	15	0.35	0.93333333		5	6	5	16		
8	2	10	15	0.35	0.93333333		5	6	5	16		

Injection Molding

$$T_1 = \frac{V}{Q}$$

T_1	Time to inject (s)
V	Part Volume (cm^3)
Q	Machine Injection Rate (cm^3/s)

$$T_2 = \frac{t_c \times D^2}{\sqrt{K}}$$

T_2	Cooling time (s)
t_C	Cooling time constant
D	Part Wall Thickness (mm)
K	HDPE Thermal diffusivity constant

$$T_{cycle} = T_1 + T_2 + T_3$$

T_3	Ejection Time (s)

	V (cm^3)	Q (cm^3/s)	D (mm)	K	t_C (s)	T_1 (s)	T_2 (s)	T_3 (s)	T_{CYCLE} (s)	Setup Time (s)	Batch Size	Cycle Time (s)	Processing Time (s)
Gear Guard Top	51490.54	700	2	0.15	1.2	73.55791429	12.39354671	4	90	900	28	123	123
Gear Guard Bottom	26172.14	700	2	0.15	1.2	37.38877143	12.39354671	4	54	900		87	87
Motor Housing	57603.86	700	3	0.15	1.2	82.29122857	27.88548009	4	115	900		148	148
Battery Housing	121063.28	700	3	0.15	1.2	172.9475429	27.88548009	4	205	900		238	238
Microcontoller Housing	2183.83	700	1	0.15	1.2	3.119757143	3.098386677	3	10	900		43	43

Trimming & Deflashing

$$T_{trim} = \frac{Time\ per\ part}{Trimming\ rate} \qquad T_{deflash} = \frac{Time\ per\ part}{Deflashing\ rate}$$

$$T_{total} = T_{trim} + T_{deflash}$$

	T_{trim} (s)	$T_{deflash}$ (s)	T_{total} (s)	Batch Size	Quantity required per unit	Processing Time (s)
Gear Guard Top	60	24	84	28	1	84
Gear Guard Bottom	60	24	84		1	84
Motor Housing	45	20	65		1	65
Battery Housing	60	24	84		1	84
Microcontoller Housing	30	15	45		1	45

Appendix 2

Process	Machine	Required No.	Cost per unit	Purchase Cost	Maintenace	Power Consumption (kW)	Depreciation	Hours in use
Injection Molding	ENGEL e-motion Injection Molder	0.9	250,000.00 €	225,000.00 €	11,250.00 €	20.00	22,500.00 €	1555.00
Drilling	HAAS VF Series CNC Vertical Mill	0.7	80,000.00 €	56,000.00 €	2,800.00 €	15.00	5,600.00 €	1416.53
CNC Turning	DMG Mori CLLX 450 CNC Lathe	1.5	150,000.00 €	225,000.00 €	11,250.00 €	15.00	22,500.00 €	1416.53
Extrusion	KraussMaffei Twin Screw Extruder	0.7	300,000.00 €	210,000.00 €	10,500.00 €	100.00	21,000.00 €	1331.67
CNC Coiling	Wafios FUL Series CNC Coiling Machine	0.1	250,000.00 €	25,000.00 €	1,250.00 €	15.00	2,500.00 €	157.78
Hobbing	Liebherr LC Series Gear Hobbing Machine	1.7	500,000.00 €	850,000.00 €	42,500.00 €	25.00	85,000.00 €	1214.31
Laser Cutting	TRUMPF TruLaser 5030 Fiber Laser Cutter	0.9	650,000.00 €	585,000.00 €	29,250.00 €	20.00	58,500.00 €	1283.33
Double End Grinding	Gardner SDG Double Disc Grinder	0.1	200,000.00 €	20,000.00 €	1,000.00 €	20.00	2,000.00 €	183.06
Gear Grinding	Reishauer RZ 410 Gear Grinding Machine	0.8	500,000.00 €	400,000.00 €	20,000.00 €	30.00	40,000.00 €	1246.94
Honing	Sunnen SV Series Vertical Honing Machine	0.1	100,000.00 €	10,000.00 €	500.00 €	10.00	1,000.00 €	200.00
Trimming & Deflashing	Romi D Series CNC Trimming Machine	0.5	60,000.00 €	30,000.00 €	1,500.00 €	5.00	3,000.00 €	703.89
Bending	AMADA HFE3i CNC Press Brake	0.2	100,000.00 €	20,000.00 €	1,000.00 €	10.00	2,000.00 €	333.33
Tapping	Brother Speedio Tapping Machine	0.1	80,000.00 €	8,000.00 €	400.00 €	5.00	800.00 €	236.11
Brush Deburring	Brush Research BRM Automated Deburring System	0.1	50,000.00 €	5,000.00 €	250.00 €	5.00	500.00 €	222.50
Pressing	Schuler H-Series Hydraulic Press	1.4	50,000.00 €	70,000.00 €	3,500.00 €	10.00	7,000.00 €	991.67

Appendix 3

Raw Materials source links

Part	Material (including source hyperlink)	Total Material to purchase (ton)	Total Cost
Frame	1060 Aluminium Alloy	7.3	16,799.14 €
Drive Shaft	Alloy Steel	1.4	2,071.53 €
Drive Shaft Gear (DIN - Spur Gear 0.8M 113T 20PA 12FW)	Cast Stainless Steel	10.5	19,254.63 €
Motor Gear (DIN - Spur Gear 0.8M 10T 20PA 12FW)	Cast Stainless Steel	0.2	367.16 €
Spring	Cast Alloy Steel	0.9	2,559.32 €
Spring Mounting Top	1060 Aluminium Alloy	1.6	3,682.62 €
Spring Mounting Bottom	1060 Aluminium Alloy	2.1	4,832.67 €
Spring Mounting Clamp	1060 Aluminium Alloy	0.3	381.30 €
Mounting Clamp	1060 Aluminium Alloy	0.6	761.58 €
Gear Guard Top	HDPE	0.5	628.12 €
Gear Guard Bottom	HDPE	0.3	377.28 €
Motor Housing	HDPE	1.3	1,632.50 €
Motor Bracket	Aluminium Alloy 5052-H32	3.4	7,071.89 €
Battery Housing	HDPE	1	1,256.24 €
Microcontroller Housing	HDPE	0.1	126.44 €
		TOTAL:	**61,802.40 €**

Manufactured parts source links

Part	Description (including source hyperlink)	Required Production Quantity	Total Cost
Electric Motor	Brushless Motor 24VDC 20A 3200rpm 400W	7000	1,356,790.40 €
Battery	24V 30Ah 7S3P Battery 30000mAh Electric Bicycle Li-ion Battery	7000	623,000.00 €
Wheel	ø250mm Pneumatic Tyre	7000	94,990.00 €
Bearing Bush	Overall Length: 28mm, Ø20mm, Ø25mm, Flange Length: 8mm	14000	138,084.80 €
Bearing	Ball Pillow Block Bearings SSBPP, Stainless Steel	14000	237,802.60 €
Bolt Type 1	Class 8.8 Hex Flange Bolt M5 x 13	28000	2,171.88 €
Bolt Type 2	Class 8.8 Hex Head Screw M2 x 8	84000	840.00 €
Bolt Type 3	Class 8.8 Hex Head Screw M4 x 10	14000	140.00 €
Bolt Type 4	Class 8.8 Hex Head Bolt M5 x 52	14000	1,260.00 €
Bolt Type 5	Class 8.8 Hex Head Screw M4 x 8	56000	560.00 €
Bolt Type 6	Class 8.8 Hex Head Screw M2 x 7	14000	140.00 €
Bolt Type 7	Class 8.8 Hex Head Screw M4 x 8	7000	70.00 €
Nut Type 1	Class 8.8 Hex Flange Nut M5	28000	560.00 €
Nut Type 2	Class 8.8 Chamfered Hex Thin Nut M2	84000	840.00 €
Nut Type 3	Class 8.8 Chamfered Hex Thin Nut M4	14000	280.00 €
Nut Type 4	Class 8.8 Chamfered Hex Thin Nut M5	14000	280.00 €
Nut Type 5	Class 8.8 Chamfered Hex Thin Nut M4	56000	1,120.00 €
Hand Fastener 1	M5 x 35	14000	10,346.00 €
Hand Fastener 2	M5 x 11	7000	4,613.00 €
Hinge Pin	40mm x 2mm	14000	5,139.68 €

Motor Controller	Voltage Input: 24V, Current Output: ≥10A, Control Method: PWM	7000	7,272.58 €
Thumb Throttle	Type: Hall Effect Sensor, Resolution: ≥256 levels, Voltage Output: 0–5V, Durability: ≥50,000 cycles	7000	35,879.08 €
Emergency Stop Button	Type: Normally Closed (NC), Voltage Rating: ≥ 24V, Design: Large Mushroom Head, Durability: ≥100,000 cycles	7000	7,616.98 €
Temperature Sensor	Range: -10°C to 80°C, Accuracy: ±1°C, Output: Digital or Analog, Response Time: ≤2 seconds, Durability: Resistant to Vibration and Heat	7000	34,475.88 €
LED Indicators	Type: RGB or Single-Color, Voltage: 3–5V, Brightness: ≥200 lumens, Durability: ≥10,000 hours	21000	5,178.92 €
DC-DC Converter	Input Voltage: 24V, Output Voltage: 5V, Output Current: ≥ 3A,Efficiency: ≥ 90%	7000	14,683.92 €
Speed Sensor	RPM Range: 0–200, Resolution: 1 RPM, Output: Analog Voltage, Durability: Resistant to Outdoor Conditions	7000	449,525.71 €
Microcontroller	Voltage: 3.3V/5V, Digital I/O Pins: ≥10, PWM Outputs: ≥2, ADC Resolution: 10-bit or more	7000	8,907.05 €
Fuse	Voltage Rating: ≥ 24V, Current Rating: ≥ 18A, Type: Blade fuse	7000	1,507.78 €
Wiring	16 - 18 AWG	12600	14,091.00 €
		TOTAL:	**3,058,167.25 €**

Appendix 4 – Marketing personnel cost calculation

Employee No.	Description	Salary	Additional Contributions								Total Cost
			Pension	Health Insurance	Long-Term Care	Unemployment Insurance	Employee Illness	Maternity Leave	Insolvency Fund	Work Accident Scheme	
Employee 1	Marketing the product and meeting sales quotas	52,850.00 €	4,915.05 €	3,858.05 €	898.45 €	687.05 €	2,166.85 €	465.08 €	31.71 €	845.60 €	66,717.84 €
Employee 2	Marketing the product and meeting sales quotas	52,850.00 €	4,915.05 €	3,858.05 €	898.45 €	687.05 €	2,166.85 €	465.08 €	31.71 €	845.60 €	66,717.84 €
Employee 3	Marketing the product and meeting sales quotas	52,850.00 €	4,915.05 €	3,858.05 €	898.45 €	687.05 €	2,166.85 €	465.08 €	31.71 €	845.60 €	66,717.84 €
										TOTAL:	**200,153.52 €**

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