POLITECNICO
MILANO 1863

Design Methods

ELECTRIC SCOOTER

TEAM 09

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1. PROBLEM DESCRIPTION

This report examines the electric scooter design process with the objective of identifying the most effective solution through a structured analysis that combines decision-making, design, and optimization tools.

The approach emphasizes a technical improvement tailored to urban mobility, responding to the increasing demand for electric scooters among daily commuters.

1.1 PROBLEM STATEMENT

In this project, the *Xiaomi Electric Scooter 4* was analyzed, identifying an area for product improvement to design a solution that addresses consumer needs.

The proposed solution aims to mitigate disturbance-induced steering and motion oscillations while complying with safety, regulatory, integration, and overall system dynamic performance constraints.

1.1.1 Problem background

Electric scooters are increasingly used for urban personal mobility, where vehicle stability is a fundamental safety requirement and is directly related to regulatory compliance, rider protection, and user acceptance.
In real-world operating conditions, electric scooters frequently encounter uneven or rough road surfaces, such as cobblestones, potholes, road joints, and surface irregularities.

Electric scooters operating on rough or irregular terrain may experience stability problems due to road-induced disturbances transmitted to the steering and front-end structure.
These disturbances can lead to undesirable oscillatory motions, degrading handling quality and perceived safety, and potentially increasing the risk of accidents.

1.2 PRODUCT DESIGN SPECIFICATION

1.2.1 Product identification

The Xiaomi Electric Scooter 4 is a foldable personal electric scooter intended for urban transportation. It is equipped with a brushless electric motor, pneumatic 10-inch tubeless tires, and an integrated electronic control system to ensure efficient propulsion and responsiveness. The scooter incorporates a dual braking system, a structural frame designed for everyday commuting, and onboard display and connectivity features for operational monitoring, making it representative of current consumer-grade electric scooters.

Figure 1: Xiaomi electric scooter

1.2.2 Market identification

The global market for electric kick scooters is experiencing strong growth driven by urbanization, increasing demand for sustainable and efficient short-distance transportation, and technological advancements in battery and motor systems.

The primary consumer segment comprises urban commuters and students seeking flexible, cost-effective solutions for last-mile mobility. A significant share of demand comes from private individual users, while commercial applications account for the remainder.

Geographically, Europe, North America, and Asia-Pacific represent key markets. Europe holds a large share of unit demand, influenced by dense cities and supportive micromobility policies, while Asia-Pacific leads in overall adoption due to rapid urbanization and strong infrastructure growth.

Due to this market scenario, Xiaomi has established itself as one of the leading brands in the electric scooter segment, competing with other major global manufacturers and positioning its products to appeal to cost-conscious consumers seeking reliable daily transportation with a balanced emphasis on performance, portability, and price.

1.2.3 Scenario and User stories

To define the design specifications, it is essential to analyze real-life usage scenarios and develop user stories. The formulation of the design model is based on three categories of scenarios:

- **Daily-use scenarios**: These scenarios involve the user’s most frequent actions.
- **Necessary-use scenarios**: These scenarios involve the types of actions that are necessary but not performed often. As these do not occur as frequently as daily

use scenarios, they can take more steps to execute than those used more often.

- **Edge-case scenarios**: These scenarios rarely occur but are of some concern for designers. Creating these types of situations might be challenging, as virtually all users will never encounter them.

	SCENARIO DESCRIPTION	**REQUIREMENTS**
Daily-use scenarios	Fabio is a 28-year-old employee working in an office in Monza. He lives in a second-floor apartment with no elevator and uses his electric scooter to go to work every day.	• Ergonomic grip • Lightweight frame • Foldability
	Sofia is a 40-year-old woman who lives in Milan and often uses her electric scooter to go grocery shopping after work.	• Extra load supporting • Front and rear lights
Necessary-use scenarios	Maria decides to go for a short trip during light rainfall, with water present on the road surface but no deep puddles.	• Adequate grip • Electrical systems remain fully operational.
	Enrico forgot to charge the scooter before going out for a ride with some friends. On the way back, the battery was almost depleted.	• Safety operation at low battery • Rideability at low battery
Edge-case scenarios	Tommaso tried to ride his electric scooter along a mountain trail. Due to an unexpected event, he is forced to stop on a steep uphill slope and then restart after a short break.	• Sufficient torque at zero speed • Adequate grip on uneven or loose surfaces.
	While riding at moderate speed, Franca encounters a pedestrian stepping into the lane and applies maximum braking force.	• No loss of steering • Adequate braking system

1.2.4 Conformity with safety and environmental legislation

The electric scooter must comply with both national and international regulations concerning electrical safety, battery handling, and environmental protection.

For the EU market, the key regulation include:

• Electrical safety: compliance with standards such as IEC 60335 and IEC 62133 for electrical systems and battery safety.
• Battery handling and transport: adherence to regulations governing lithium-ion batteries, including UN 38.3 and relevant IEC standards.
• Vehicle safety: conformity with EN 17128 for personal light electric vehicles, covering mechanical integrity, braking performance, and stability.
• Electromagnetic compatibility (EMC): compliance with the EMC Directive 2014/30/EU to ensure proper electromagnetic behavior.
• Environmental protection: compliance with directives such as RoHS (2011/65/EU) and WEEE (2012/19/EU) to limit hazardous substances and ensure proper end-of-life disposal.
• Market access and certification: fulfillment of CE marking requirements for sale within the European market.

2. DESIGN PROCESS

2.1 MARKET ANALYSIS

The electric scooter market is characterized by a wide range of solutions aimed at addressing urban micromobility needs. These solutions can be categorized into three main segments based on the primary value they provide to customers:

a) Portability and ease of use
b) Riding comfort and stability
c) Structural safety and robustness

2.1.1 Portability and ease of use

Portability and ease of use constitute a primary value proposition in the electric scooter market, particularly for urban users who frequently combine scooters with public transportation or need to carry them over short distances. This functional requirement is mainly fulfilled through low overall weight and foldability, which allows scooters to be easily transported, stored, and handled in constrained environments.

To address this demand, many widely adopted commercial products emphasize lightweight construction and compact folding solutions. Models such as the Xiaomi Electric Scooter series, Segway–Ninebot commuter scooters, and similar urban-oriented designs typically feature aluminum alloy frames and quick-folding steering columns, enabling users to fold the scooter within seconds and reduce its size for storage under desks, in car trunks, or on public transport.

The prevalence of lightweight and foldable solutions among best-selling electric scooters demonstrates that portability is a key driver of user adoption and market competitiveness. As a result, low weight and ease of handling are consistently prioritized by manufacturers as essential characteristics for urban electric scooters.

Figure 2: Xiaomi Electric Scooter

Figure 3: Folding Xiaomi E-scooter

2.1.2 Riding comfort and stability

Riding comfort and stability represent another key value dimension in the electric scooter market, as they directly affect user confidence and perceived safety during everyday operation. Urban riding conditions typically involve uneven pavements, curbs, and frequent braking events, making stable and predictable vehicle behavior a primary expectation for users.

To address this demand, many popular electric scooters are equipped with higher motor power to ensure smooth acceleration and adequate performance on slopes, reducing sudden speed variations that may compromise stability. In addition, manufacturers adopt different tire solutions depending on the intended use: pneumatic tires are widely used in commuter models for their improved shock absorption and traction, while solid tires are often chosen for durability and reduced maintenance.

More advanced models further enhance comfort and stability through the integration of front or rear suspension systems, which help isolate the rider from road irregularities. The widespread adoption of these solutions in commercial products highlights how riding comfort and stability are central factors in the market positioning of electric scooters.

2.1.3 Structural safety and robustness

Structural safety and robustness have become increasingly important value propositions in the electric scooter market, particularly as scooters are subjected to higher speeds, heavier users, and more demanding urban environments. Users expect scooters to withstand repeated loads, braking forces, and road irregularities while maintaining stable and reliable behavior over time.

In response to this demand, many manufacturers emphasize reinforced structural components and conservative load ratings in their product designs. Common market solutions include the use of high-strength aluminum alloy frames, oversized steering columns, and reinforced folding mechanisms designed to limit excessive deformation during operation. Additionally, manufacturers often specify maximum rider weight limits and durability-oriented design features to convey reliability and safety to consumers.

The widespread adoption of reinforced structures and safety-oriented design choices among commercially successful electric scooters indicates that structural robustness is a key factor influencing user trust and market competitiveness, especially in urban and commuter-focused applications.

2.2 CUSTOMER REQUIREMENTS LIST

The selected electric scooter is intended for urban mobility, providing an efficient and flexible solution for daily commuting and short-distance travel. The product is designed to integrate seamlessly into city environments while maintaining adequate performance, safety, and manufacturability.

Based on the market analysis and project constraints, the main customer requirements have been identified and structured as follows.

	Requirements
Design Usability	▪**Portability and ease of transport**: the scooter should have a total weight not exceeding **25 kg**, allowing users to handle it during short transfers, stairs, or public transportation use. ▪**Foldability**: the scooter should feature a foldable or partially collapsible structure to reduce its overall size for storage in confined spaces such as apartments, offices, or vehicle trunks. ▪**Ease of use**: intuitive operation, including simple folding/unfolding procedures and user-friendly controls, should be ensured.
Comfort and Stability	▪ **Riding comfort**: the scooter should provide a comfortable riding experience on typical urban surfaces, minimizing discomfort caused by uneven pavements or minor obstacles. ▪ **Stability**: stable and predictable behavior during acceleration, braking, and cornering should be guaranteed to increase user confidence. ▪ **Low physical effort**: the scooter should require minimal physical effort from the user, ensuring smooth operation during everyday commuting.

Performance	▪ **Adequate motor performance**: the scooter should provide sufficient power for urban use, enabling smooth acceleration and the ability to handle moderate slopes. ▪ **Reliable range**: the battery system should support typical daily commuting distances without requiring frequent recharging. ▪ **Efficient braking system**: reliable and responsive braking should be ensured under both dry and wet conditions.
Structural Integrity and Safety	▪ **Structural reliability**: the scooter should withstand expected service loads, including rider weight, braking forces, and road-induced vibrations, without compromising safety. ▪ **Compliance with standards**: the design should comply with relevant safety and regulatory standards for personal light electric vehicles. ▪ **Perceived robustness**: the scooter should convey a sense of solidity and durability, enhancing user trust during operation. ▪**GPS tracking**: system with remote monitoring and dedicated app for real-time tracking and control if the bike is theft.
Sustainability	▪ **Use of standard components**: approximately 80% of the components should be commercially available parts to simplify sourcing and reduce production costs. ▪ **Ease of assembly**: the design should allow straightforward manufacturing and assembly processes. ▪ **Durability of parts**: long-lasting components that reduce the frequency of replacements and waste.

2.3 PRODUCT DISSECTION

The Product Dissection technique enables a comprehensive analysis of a product's operational and usage functions, allowing the identification of factors that affect its performance and user interaction.
This approach makes it possible to examine how different subsystems work together to transform energy, materials, and signals into functional actions, ensuring that the product effectively satisfies user requirements.

2.3.1 Activity domain

The first step in this analysis is to define the activity domain through a diagram that maps the e-scooter's key functions, illustrating its overall operation and interaction with the user.

This analysis, based on function domain theory, does not merely consider the product's physical form but also examines the system behavior and functional transformations, providing a deeper understanding of the e-scooter's behavior and performance.

At the first stage, the e-scooter is modeled as a "black box", where kinetic and electrical energy inputs are transformed into outputs such as motion and energy dissipation.

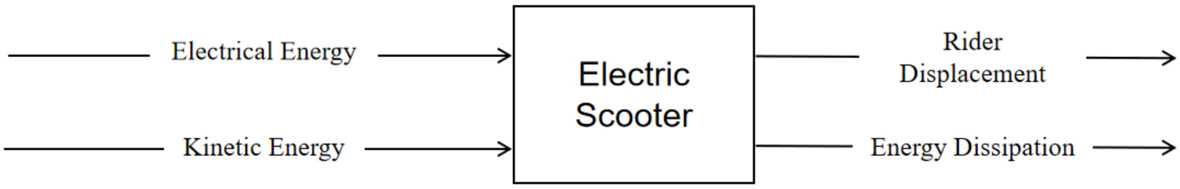


Figure 4: Activity Domain Black Box

Once the global function of the system has been identified, it is further decomposed into a set of functional activities that contribute to the execution of the scooter's primary task. As illustrated in *Figure 5*, rider intentions are translated into actions such as regulating speed and direction or applying braking, which in turn allow or deny wheel motion and ultimately result in the movement of the scooter. This representation clarifies the logical sequence of activities required to ensure controlled and stable vehicle operation.

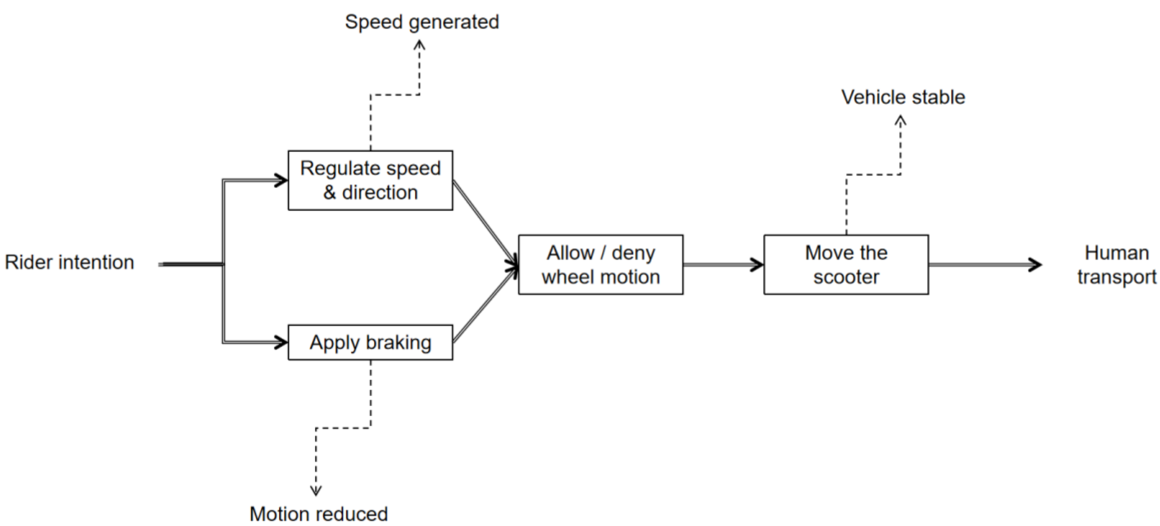


Figure 5: Activity Domain Functional Activities

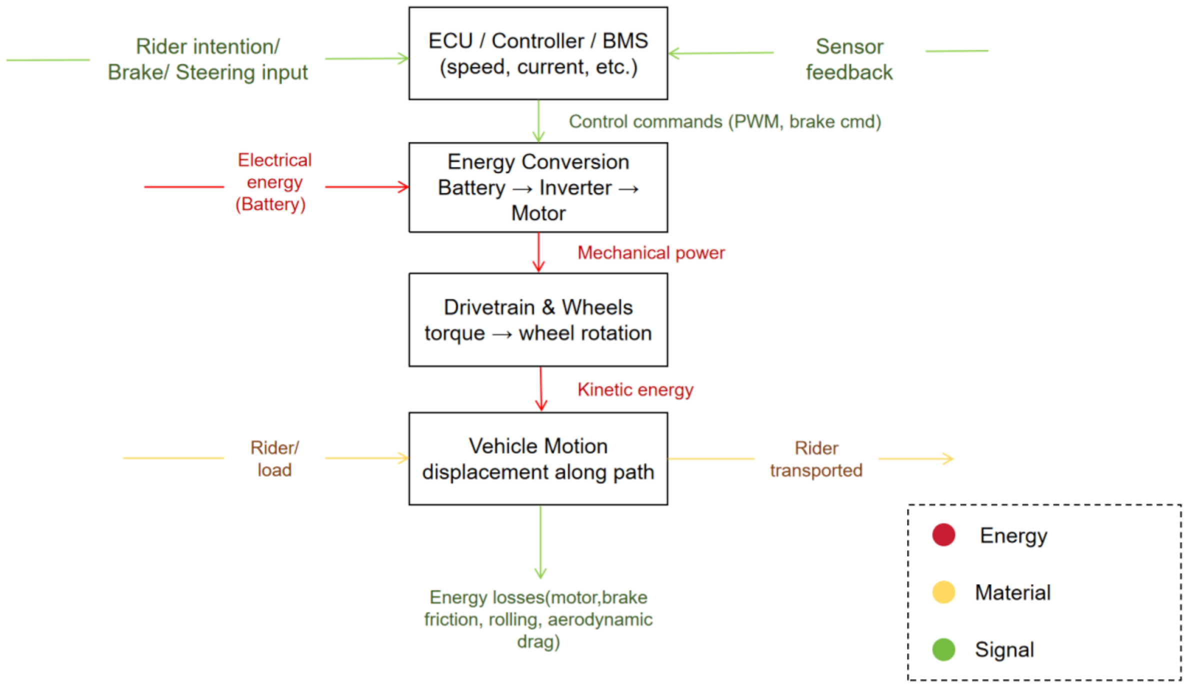


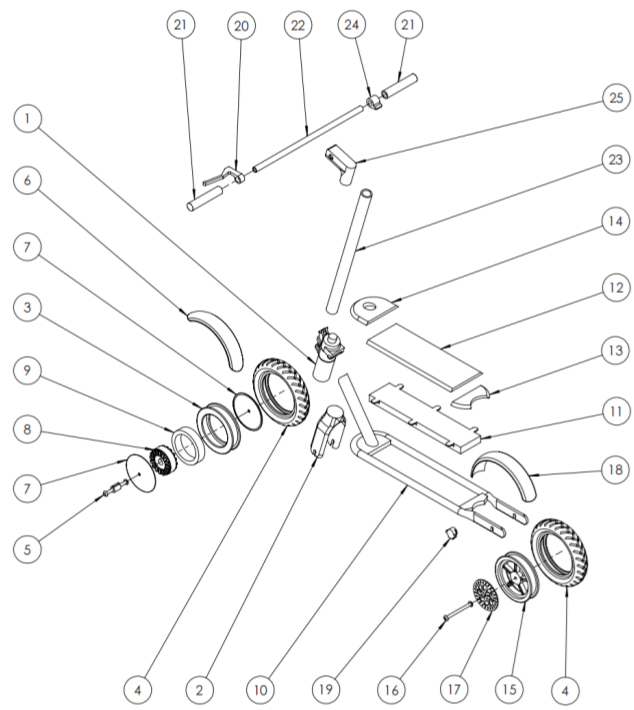
Figure 6: EMS

To better understand how these activities interact, the activity domain is further analyzed through an energy–material–signal flow representation, shown in *Figure 6*. This diagram highlights the exchange of electrical energy, control signals, and mechanical interactions between the rider, the control system, the energy conversion chain, and the drivetrain. Electrical energy stored in the battery is converted into mechanical power at the wheels, while control signals regulate acceleration and braking based on rider inputs and sensor feedback. At the same time, rider load and resistive forces influence the resulting vehicle's motion.

By combining black-box modeling, functional decomposition, and flow-based interaction analysis, the activity domain provides a comprehensive understanding of how the electric scooter fulfills its primary function. This structured representation forms the basis for the subsequent organ domain analysis, where the identified activities are mapped onto physical subsystems.

2.3.2 Organ domain

The Design Structure Matrix (DSM) is a visual tool used to map and analyze the dependencies between components, tasks, or activities within a system. By structuring relationships in a square matrix, the DSM highlights critical interconnections, streamlines workflows, and enhances modularity in design.



ITEM NO.	PART NUMBER	QTY.
1	stabilizer	1
2	fork	1
3	rim	1
4	tyre	2
5	front axle	1
6	front fender	1
7	cover	2
8	stator	1
9	rotor	1
10	frame	1
11	battery box	1
12	main deck	1
13	rear deck	1
14	front deck	1
15	rear wheel	1
16	rear axle	1
17	brake disc	1
18	rear fender	1
19	brake caliper	1
20	brake lever	1
21	grip	2
22	handlebar	1
23	steering column	1
24	throttle lever	1
25	stem	1

Digital Design	Section: CM1
Proff: Giorgio Colombo, Roberto Vigano', Alessandro Stefanone	
Project Name: Xiaomi Electric Scooter 4	
Group Number: 9	Date: 06/02/2026
Students Names: Alessandro Dell'Orto, Tianci Lei, Jingyue Ni, Luca Ricciardi, Murat Taskin	
Title: Exploded View BOM	
Drawing Number: 2	
Scale 1:10	

Grouping	Row Items	Column Items	Deck	Main frame	Battery box	Side stand	Rear fender	Front tire	Front rim	Motor housing	Rear tire	Rear rim	Tube（handlebar）	Grips	Hook	Stem	Folding mechanism	Front fender	Fork	Battery pack	BMS	Motor	Control unit	Throttle	Cables	Dashboard	Lights	Brake lever	Brake cable	Brake caliper	Disc brake
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Frame	Deck	1		×	×																										
Frame	Main frame	2	×		×	×	×	×	×	×	×	×							×											×	
Frame	Battery box	3	×	×																×	×										
Frame	Side stand	4		×																											
Frame	Rear fender	5		×																											
Wheels	Front tire	6		×					×																						
Wheels	Front rim	7		×				×		×									×												×
Wheels	Motor housing	8		×					×										×			×									
Wheels	Rear tire	9		×								×																			
Wheels	Rear rim	10		×							×																				×
Steering System	Tube（handlebar）	11												×	×	×								×	×	×		×			
Steering System	Grips	12											×																		
Steering System	Hook	13											×																		
Steering System	Stem	14											×				×		×												
Steering System	Folding mechanism	15														×															
Steering System	Front fender	16																	×												
Steering System	Fork	17		×					×	×						×		×													
Electrical System	Battery pack	18			×																×		×								
Electrical System	BMS	19			×															×			×								
Electrical System	Motor	20								×													×								
Electrical System	Control unit	21																		×	×	×		×		×	×	×			
Electrical System	Throttle	22											×										×								
Electrical System	Cables	23											×																		
Electrical System	Dashboard	24											×										×								
Electrical System	Lights	25																					×								
Braking System	Brake lever	26											×										×						×		
Braking System	Brake cable	27																										×		×	
Braking System	Brake caliper	28		×																									×		×
Braking System	Disc brake	29							×			×																		×	

Figure 7, 8: Design Structure Matrix, Exploded view of the e-scooter showing main organs

The exploded view is not intended as a detailed mechanical drawing, but as a system-level representation supporting the interpretation of the DSM clusters and their correspondence to real product organs.

By implementing the DSM matrix, we identified five primary clusters representing the e-scooter organs. Based on them, we established the connection between the organ domain and the activity domain, illustrating how the components interact with the e-scooter's primary functions.

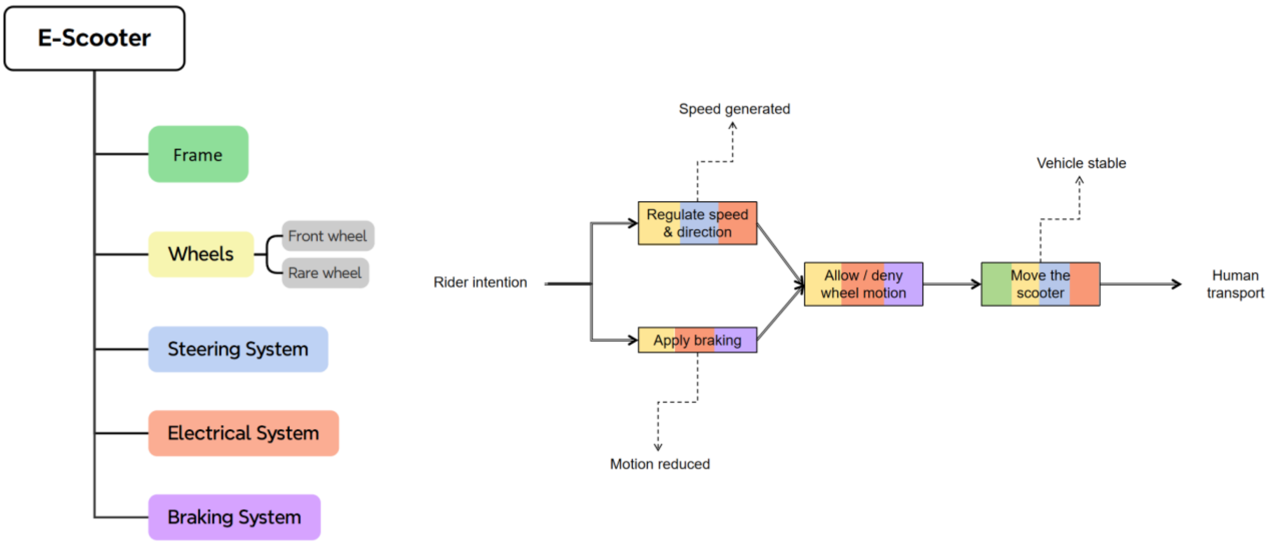


Figure 9: Organ Domain

2.3.3 Part domain

The diagram below breaks down the e-scooter into its main subsystems and specific components. It starts with the primary entity (the e-scooter) and is subsequently divided into the following macrosystems:

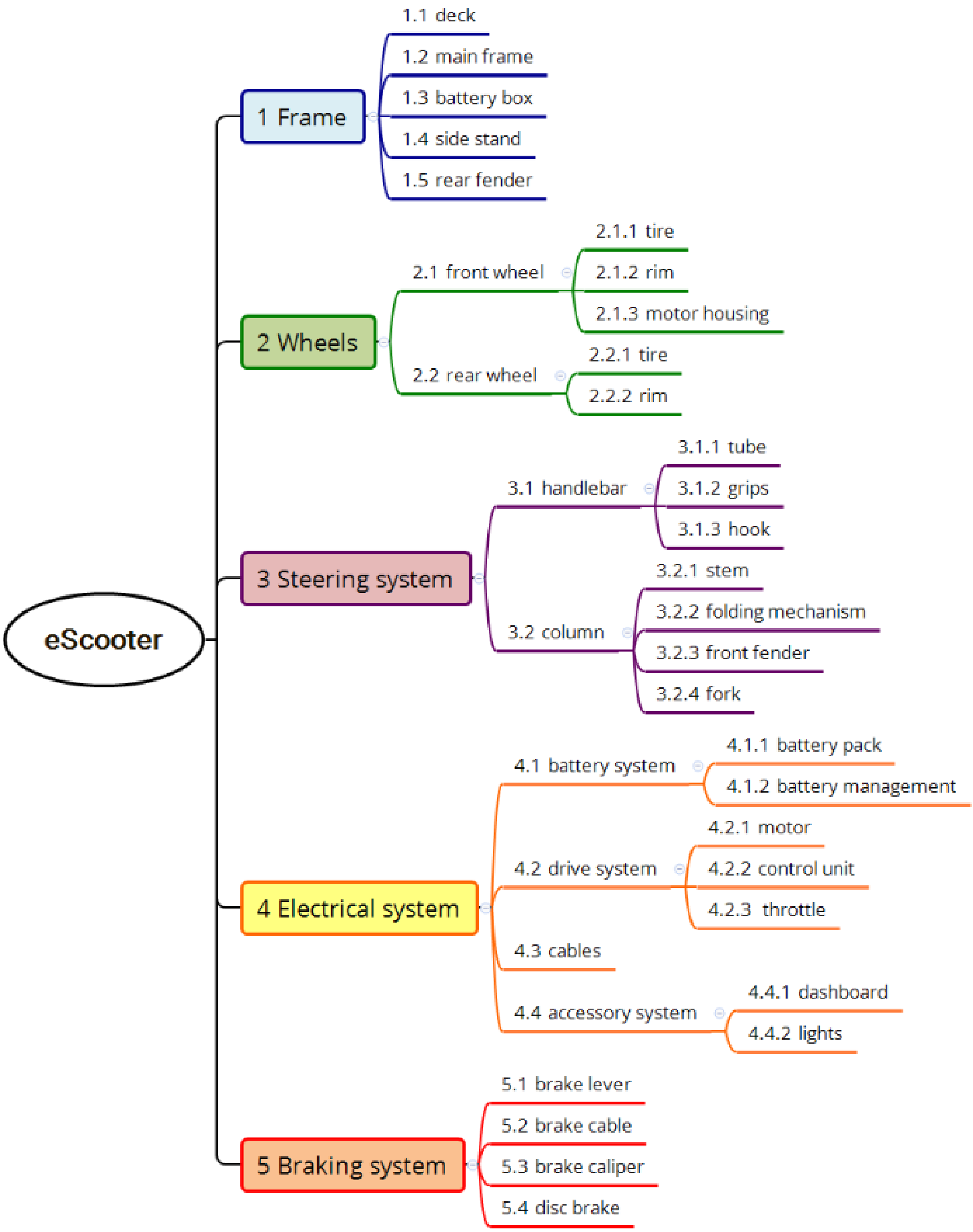


Figure 10: Part Domain

This analysis provides a clear view of both functional and physical connections illustrating how each element contributes to the product's overall functionality and modes of use.

2.4. QUALITY FUNCTION DEPLOYMENT

Quality Function Deployment (QFD) is a planning and team problem-solving tool adopted to convert customer requirements into technical specifications, ensuring that customer needs are accurately embedded in the design process. As the core instrument of the QFD methodology, the House of Quality matrix has been applied as follows:

- Customer requirements were assigned an importance level from 1 to 5 with the following scale: 1 = Marginal, 2 = Preferable, 3 = Important, 4 = Very important and 5 = Essential. This helps identify the technical requirements that are critical to meet customer needs.
- The relationship between customer needs and corresponding technical requirements was assessed using a point system: 1 point indicates a weak correlation, 3 points a moderate correlation, and 9 points a strong correlation.
- The scooter being analyzed was compared with two other models. Each model was evaluated based on customer satisfaction, using a scale of 1 to 5: 1 = Most unsatisfied, 2 = Unsatisfied, 3 = Quite satisfied, 4 = Satisfied, 5 = Very satisfied

The Xiaomi electric scooter 4 was compared with two competitor models: *iScooter i8 Electric Scooter* and *Segway Ninebot E2 Plus E*.

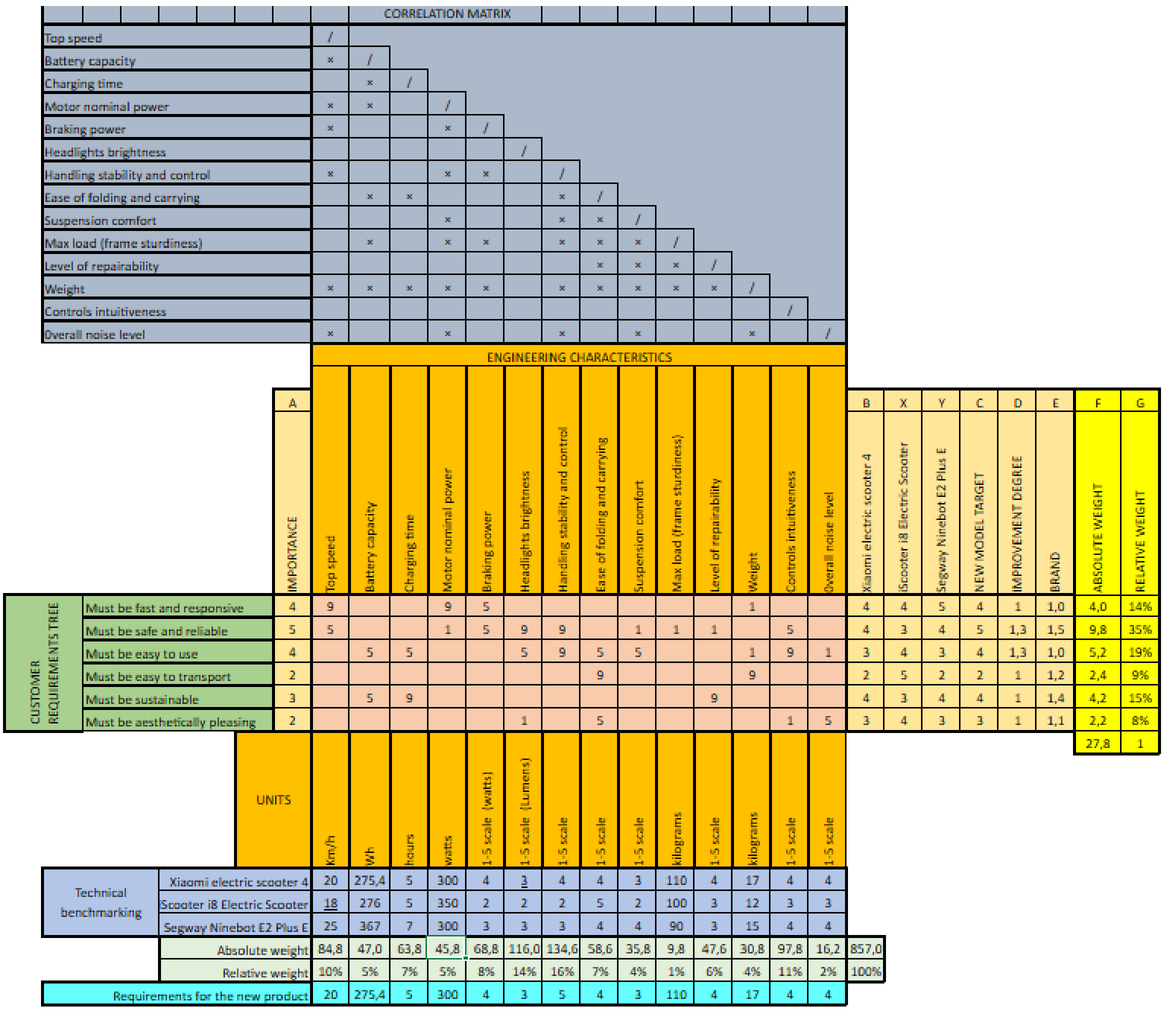


Figure 11: House of Quality

2.5 DECISION MAKING

2.5.1 Identification of the improvement direction

From the Quality Function Deployment (QFD) analysis and the user scenarios defined in the early design phases: responsiveness, ease of use, safety and reliability emerged as critical customer requirements for urban electric scooters.

While the scooter exhibits acceptable compliance to these requirements in most riding conditions, riding instability phenomena arise in specific circumstances, such as abrupt acceleration, sudden braking, maneuvering in dense urban environments and driving on rough or uneven terrain.

User scenarios

In typical urban use cases, riders frequently operate the scooter:

- starting and stopping at traffic lights,
- maneuvering in crowded pedestrian areas,
- riding on uneven pavements and on rough terrain,
- performing quick direction and speed changes.

In these scenarios, users often report feeling a sense of unsafety caused by reduced lateral stability and the need for continuous balance corrections.

Customer requirement

Based on the Customer Requirements List and QFD results, the following requirements are directly affected and should be considered to identify the improvement direction.

- Improved riding and steering stability for safety reasons.
- Reduced physical and cognitive effort required to maintain balance.
- Increased perceived safety for every riding condition.

Safety and Confidence issue

Usually, the lack of effective riding stability does not lead to immediate safety hazards, but it negatively impacts user confidence, increasing the effort required to maintain balance, potentially discouraging adoption and limiting usability in urban conditions.

Therefore, a dedicated design decision addressing stability becomes necessary.

2.5.2 Definition of stability improvement strategies

The decision focuses on how to improve lateral stability of the scooter without altering its fundamental architecture or compromising key attributes such as portability, weight, maneuverability, responsiveness, and ease of use.

Stability-related requirements

The selected solution is required to improve lateral stability in everyday operating conditions while reducing the physical effort demanded by the rider during balance corrections. At the same time, it must enhance perceived safety and rider confidence without compromising maneuverability or the overall riding experience.

To remain consistent with the original product concept, the solution should not introduce a significant increase in mass, nor require major modifications to the main frame or steering geometry.

These constraints ensure that the proposed improvement remains compatible with the existing architecture and preserves key attributes such as portability.

Design alternatives considered

The following alternatives were evaluated at both system and subsystem level:

Design Alternative	Description	Design Direction
Geometry modification	Stability improvement achieved through modifications of the scooter's geometric parameters.	• Increase of wheelbase • Variation of head tube angle
Wider deck / lower center of gravity	Enhancement of stability by increasing the support base and lowering the center of gravity.	• Increased standing surface • Redistribution of mass to lower the CG
Active electronic control	Stability enhancement through sensor-based control and active actuation.	• Sensors combined with control algorithms • Active stabilization via actuators
Damping system steering stabilizer	Reduction of steering oscillations through additional damping at the steering interface.	• Passive steering damper • Semi-active steering damper
Passive spring steering stabilizer	Stability improvement obtained through a purely mechanical auxiliary element.	• Small auxiliary stabilizing element • No active control or external power required

These alternatives were selected to cover a broad spectrum of possible solutions, ranging from structural changes to control-based and purely mechanical approaches.

2.5.3 Decision criteria

The Pugh Chart methos is used to identify the most promising design concepts among the alternatives generated; the alternatives are compared in an evaluation chart.

Criteria	Geometry modification	Wider deck or lower CG	Active electronic control	Damping steering stabilizer	Spring Steering stabilizer
Small mass increment	-2	-2	-1	0	0
Steering stabilization effectiveness	+1	+1	+2	+1	+2
Compliance to original architecture	-1	-1	0	0	0
Number of unchanged components	-2	-2	-1	-1	-1
Unchanged vehicle main dimensions	-2	-2	0	0	0
Usability with empty battery	+1	+1	-1	+1	+1
Ease of implementation to current state	0	-1	0	+1	+1
Cost of the solution	-1	-1	-2	-1	-1
Net score	-6	-7	-3	+1	+2

The evaluation chart above shows that the most suitable improvement direction involves some sort of damping or spring steering stabilizer.

Figure 12,13, 14: Tangent Damper Stabilizer, Tangent Spring Stabilizer and Axial Spring Stabilizer

The three stabilizers above offer different types of steering stabilization.

1) The **damping steering stabilizer** offers great riding safety at high speeds because its damping system is designed to absorb high frequency oscillations that usually occur in electric scooters designed to reach really high top speeds.

This solution is not suited for the design improvement. Because the requirements impose an improved steering stability in every riding condition and not only at high speed.

2) The **tangent spring steering stabilizer** would improve steering stability at every speed, but the stabilizing torque it produces increases linearly with the steering angle. This property is not optimal for the intended use scenario of the scooter.

3) The **axial spring steering stabilizer** is the most suitable solution, because its cylindrical cam design generates a small torque at the smallest steering angles for maximum responsiveness and maneuverability, while at the highest steering angles it produces the maximum torque. This solution generates the highest torques only when the front wheel suffers sudden high deflections due to uneven or rough terrain; this stabilizer satisfies the product requirements.

3. EMBODIMENT

3.1 EMBODIMENT DESIGN OVERVIEW

3.1.1 Role of the stabilizer in the overall architecture

Primary function of the stabilizer

The primary function of the steering stabilizer is to enhance steering stability under all riding conditions, including low-speed maneuvering, transitional phases (starting and stopping), and high-speed riding, without compromising rider control or steering responsiveness.

The stabilizer acts as a passive mechanical element that introduces a controlled restoring torque on the steering system. This torque is designed to be non-linear with respect to the steering angle, providing minimal resistance near the neutral position to preserve maneuverability, while progressively increasing at larger steering deflections to suppress undesired oscillations and sudden disturbances induced by uneven road surfaces.

Allocation within the e-scooter system architecture

Within the overall e-scooter system architecture, the steering stabilizer is allocated as a local passive subsystem within the steering assembly, positioned at the interface between the steering column and the head tube.

The stabilizer operates independently of electronic control systems and does not require sensors, actuators, or power supply. Its performance is intrinsically coupled to the mechanical configuration of the steering system and is tuned through geometric parameters.

3.1.2 Interaction with existing subsystem

From a system perspective, the stabilizer interacts primarily with:

- the steering column and handlebar assembly, through which steering inputs are applied;
- the front wheel and fork, which transmit road-induced disturbances;
- the folding mechanism and cable routing, which impose packaging and kinematic constraints.

The stabilizer does not alter the fundamental steering kinematics or limit the steering range, but rather improves the steering behavior by modifying the torque response to disturbances. In this way, it complements existing structural and geometric design features of the scooter, contributing to overall riding safety and stability without increasing system complexity.

3.2 CONFIGURATION DESIGN

3.2.1 Stabilizer configuration

The stabilizer is integrated in the head tube of the frame, in a way that minimizes the number of components that need to be modified to house the new parts.

A straight slot has been cut in the tube of the fork to accommodate the axial movement of two rollers, connected to the follower by a pin. The contact between the rollers and the lateral surface of the slot transfers the tangential component of the pressure forces from the cam to the fork.

The axial movement of the follower compresses a spring that has been designed to generate a stabilizing torque around the steering axis.

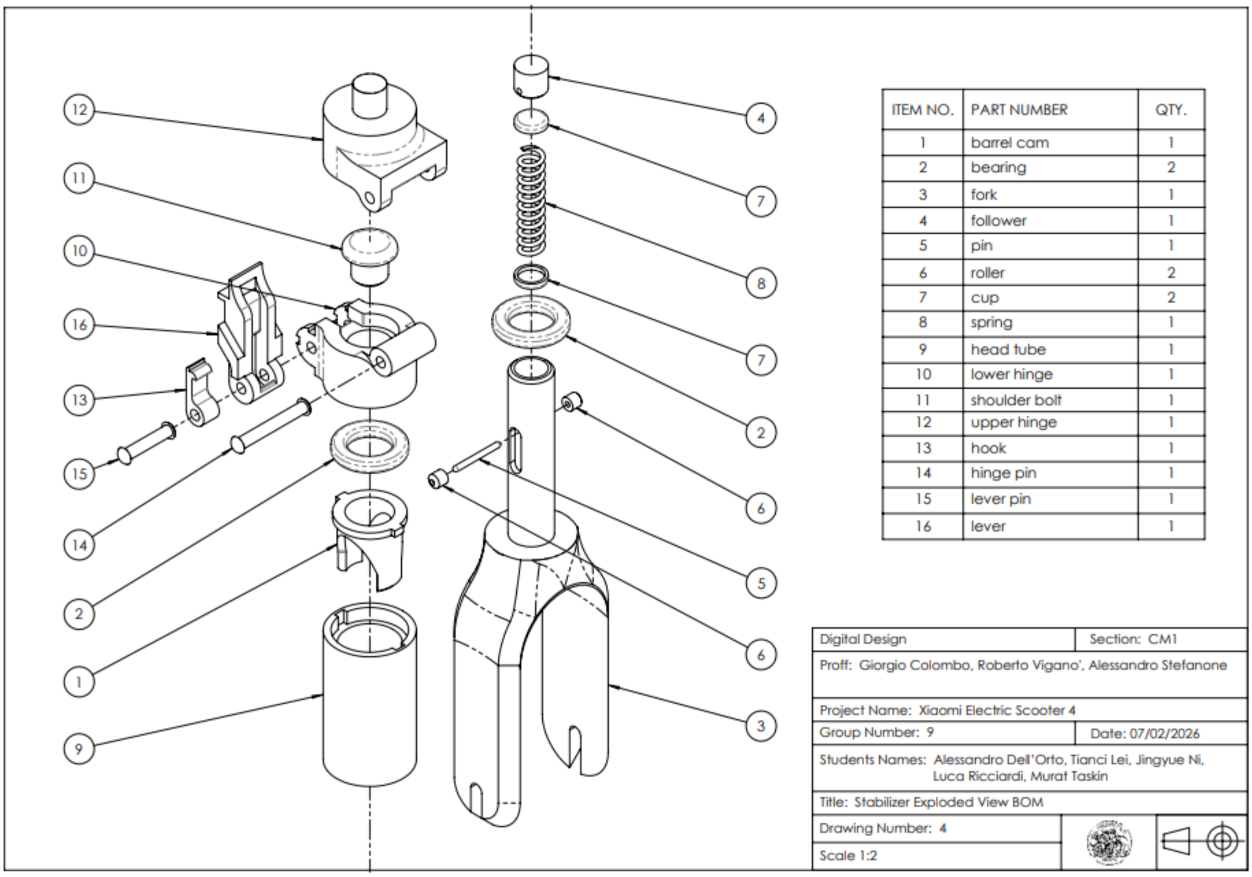


Figure 15: Stabilizer Exploded View BOM

At the end of the report there is a more comprehensive selection of technical drawings, useful to better understand the geometry of the proposed solution.

3.2.2 Interfaces and constraints

Functional surface

Functional surfaces are the regions where the stabilizer performs its intended functions (load transfer, relative motion, torque generation, and protection). In the section views (A-A and B-B), the following surfaces are function-critical and therefore require explicit design attention (material pairing, surface finish, tolerances, and protection):

- Steering-axis guiding / bearing surfaces (pivot region): the coaxial cylindrical guiding surfaces that constrain the stabilizer core to move/rotate correctly with respect to the steering axis (visible as the concentric sleeves and the central shaft region in both A-A and B-B). These surfaces govern clearance, friction, and wear, and must be controlled in coaxiality/concentricity and surface finish (Ra). A robust pairing is typically polymer bushing (or liner) against anodized Al / hardened steel, to ensure low friction and stable wear.

- Cam–follower contact surfaces (torque generation): the barrel cam profile surface and the follower/roller contact surfaces (the contact pair that converts steering rotation into axial displacement). This interface is the core of the stabilizing characteristic; it requires controlled roughness, local hardness/wear resistance, and a geometry consistent with the intended pressure angle. Edge-breaks and contact-track quality are essential to avoid stick-slip and to ensure repeatable torque response.

• Roller–guide (slot) load-transfer surfaces: the roller outer surfaces and the two lateral faces of the fork slot that provide guidance and transmit the tangential component of the cam reaction into the fork (this is the functional pair that prevents relative slip and defines the force path). These surfaces require adequate flatness/parallelism (slot faces), controlled clearance (to prevent jamming but limit rattle), and burr-free edges (chamfers) to avoid scoring and contamination trapping.

• Spring seat and axial load-path surfaces: the upper and lower spring seats/caps, and the planar/annular contact faces that carry the spring force into the surrounding structure (clearly visible where the coil spring bears on the caps). These surfaces need sufficient bearing area, local fillets, and alignment control to prevent eccentric loading (which increases friction and accelerates fatigue). Surface finish and squareness affect repeatability of torque output.

• Pin/bearing surfaces for roller rotation: the pin–roller bore cylindrical interface that allows the rollers to rotate with minimal friction. This pair governs rolling efficiency and wear debris generation. Typical focus: diameter tolerance (clearance fit), roundness, and wear-resistant pairing (e.g., stainless steel pin with polymer roller or hardened steel roller with bushing).

• Environmental protection and safety-adjacent surfaces: the interfaces where covers/seals (if present) would sit around the top entry region and the outer edges/shoulders that could be exposed during folding/handling. These regions should be designed for contamination control (labyrinth/cover contact features, drainage) and for user safety (edge breaking, no sharp corners, adequate clearance to avoid pinch points).

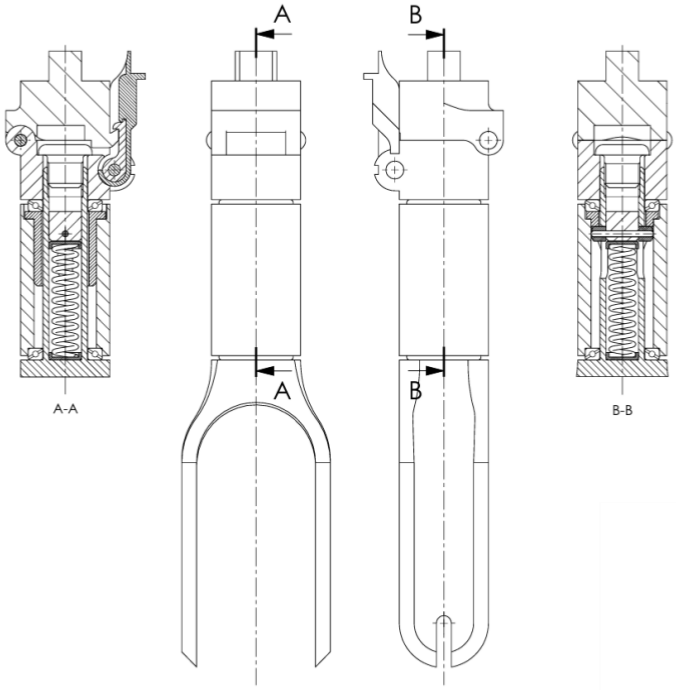
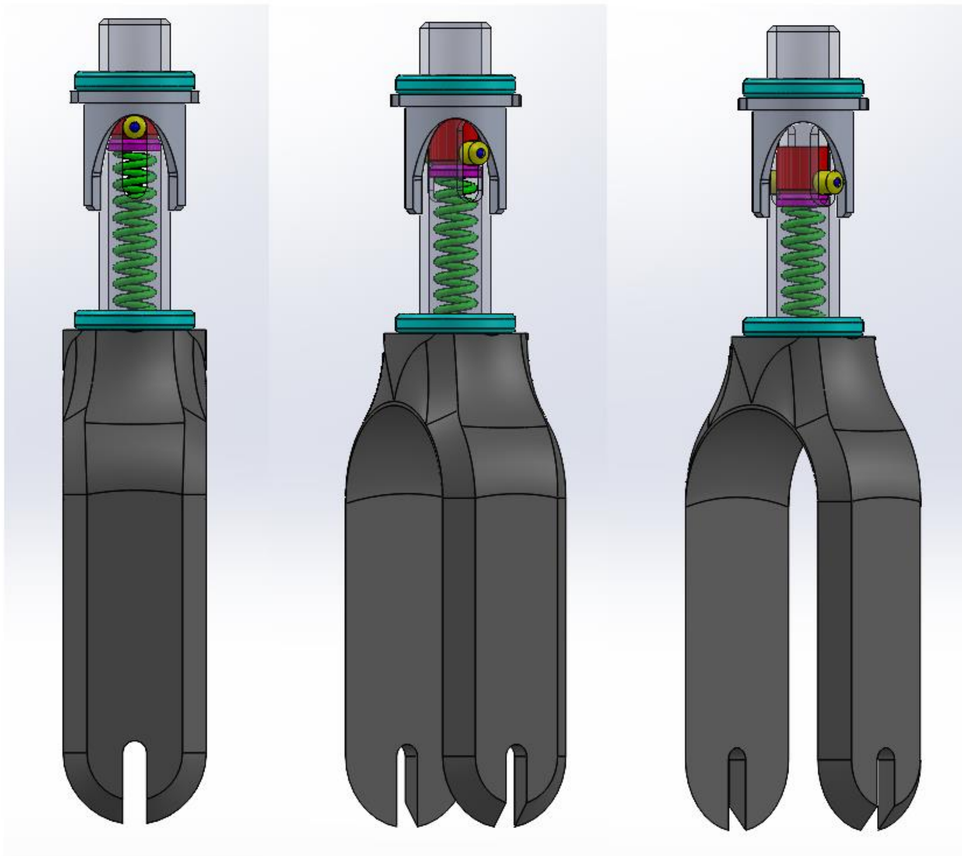
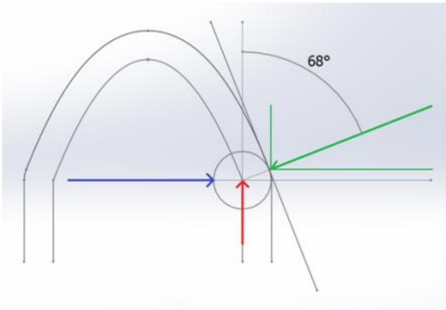


Figure 16: Stabilizer Section Views



The final improvement solution consists in a steering stabilizer, based on the working principle of a follower that moves along the parabolic profile of a cylindrical cam, to compress a spring that generates a stabilizing force, aiming to always restore the steering system alignment to the scooter frame.



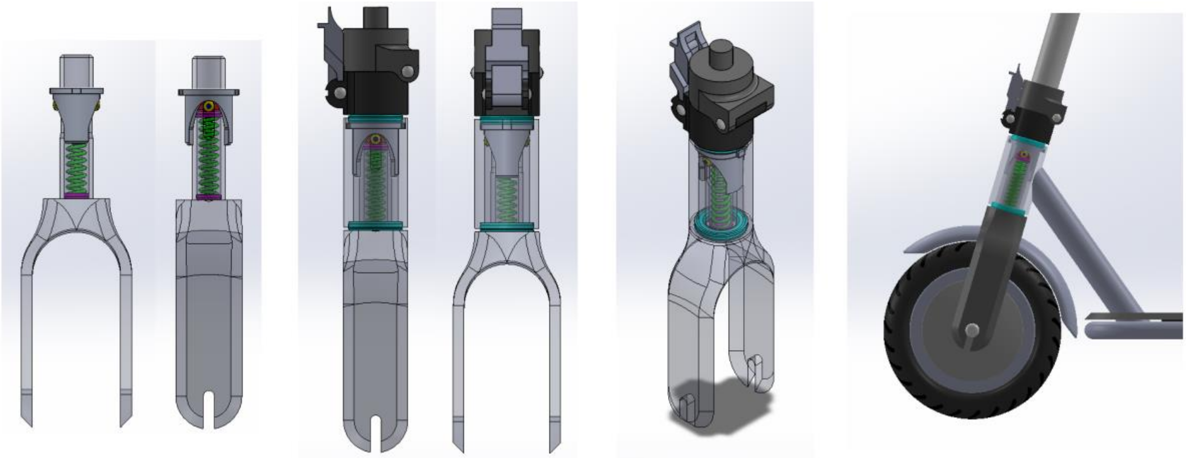


Figure 17, 18, 19: Spring Compression, Pressure Angle and Steering Stabilizer Location

3.3 FINAL DESIGN

For the steering stabilizer proposed, a comprehensive series of detailed technical drawings were created to communicate the geometry of the components, their relative position, and their assembling order. The barrel cam has been dimensioned to correctly interact with the follower and to generate the desired torque on the steering axis.

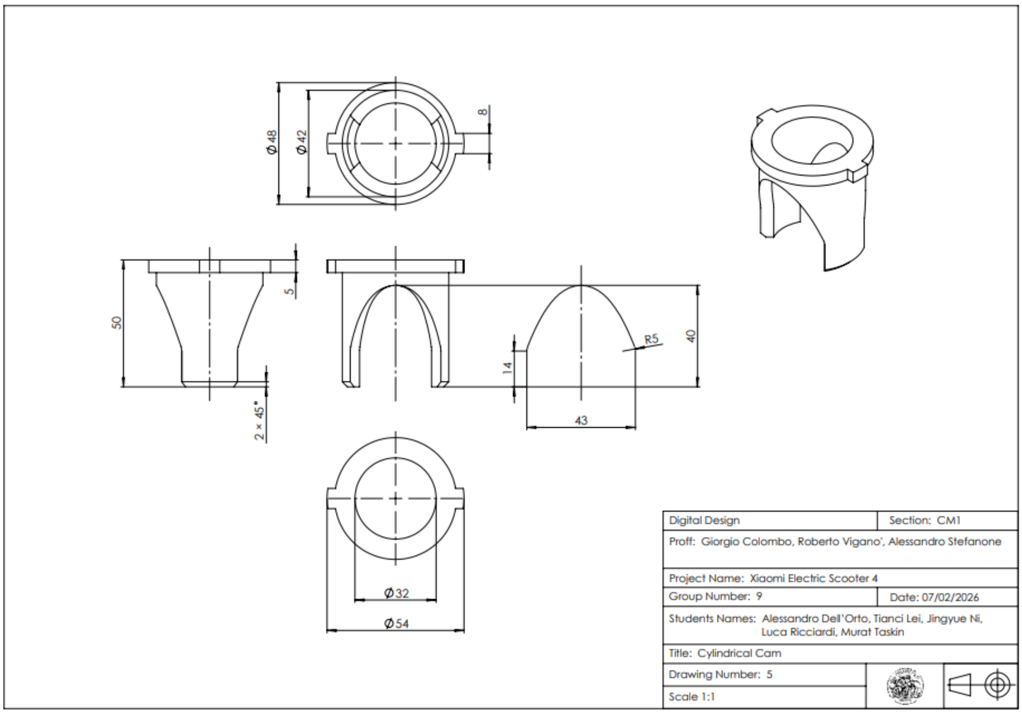


Figure 20: Cylindrical Cam

3.4 MATERIAL SELECTION

During the design of the stabilizer components, to ensure the correct operation of every part, the material of each component was selected. The parts enduring the highest stresses are made of stainless steel; these parts comprehend: the cam, the follower, the pin connecting the rollers to the follower and two caps holding the spring in place.

The fork and the head tube are made of aluminum 6061-T6 as in the original design.

The spring is made of spring steel, and the rollers should be made of a tough low friction polymer like Teflon (PTFE).

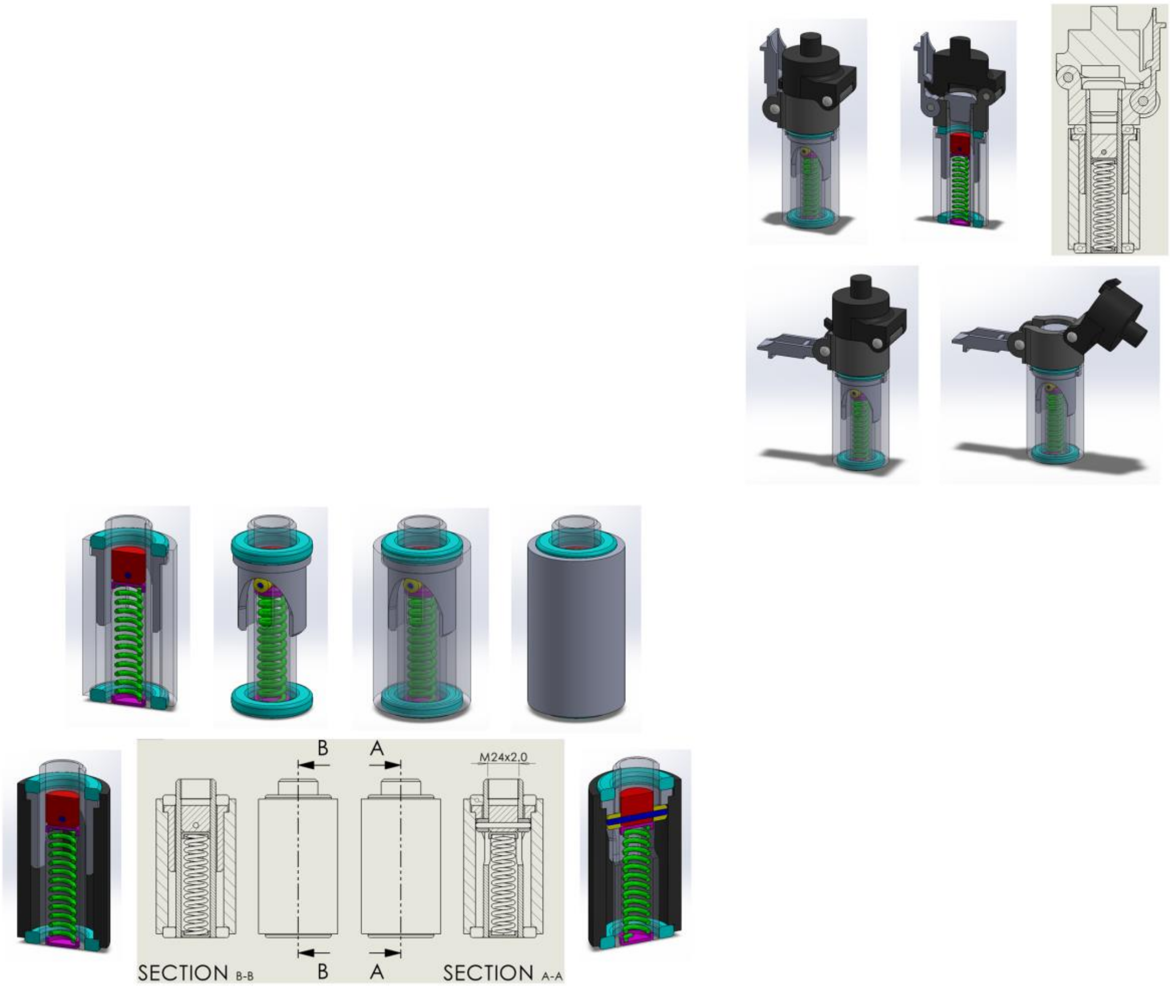


Figure 21, 22: Stabilizer 3D Section Views and Opened Hinge Configuration

4. SIMULATION RESULTS

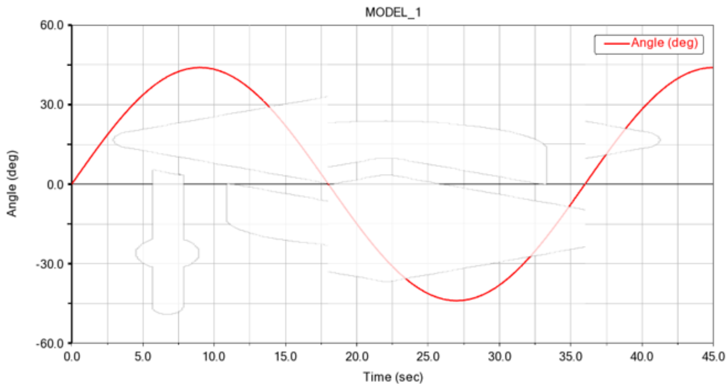
4.1 KINEMATIC ANALYSIS

The kinematics of the steering stabilizer were studied using the Adams software.

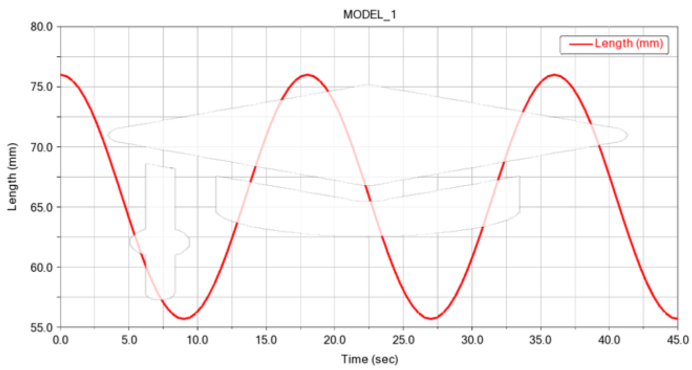
Adams was used to define the assembly for the components, using the appropriate constraints, and to study the relative motion of every part of the stabilizer.

A sinusoidal motion was imposed to the steering angle with the following function:

```
44d * SIN(10d*time)
```

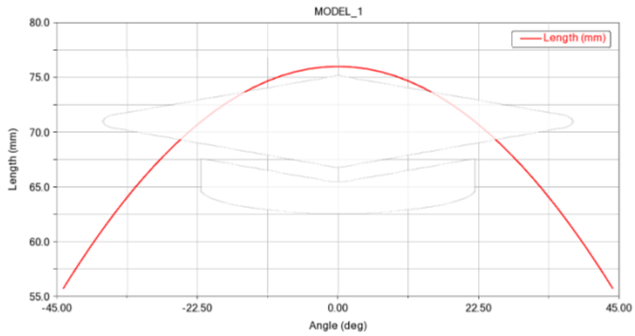


And then the length of the spring over time, equal to the distance of the cups holding it, was plotted to show the compression cycles of the spring as the steering angle varies.

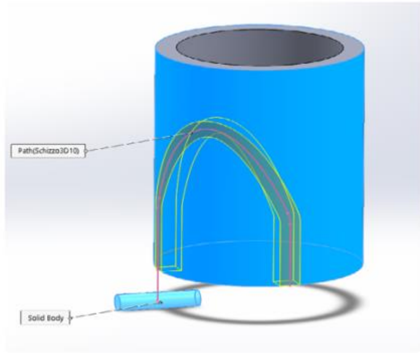


The measurements obtained with Adams were also useful to extract the length of the spring as a function of the steering angle. This is shown in the diagram below.

The table on the right side of the diagram contains the cylindrical coordinates of the parabolic path the rollers trace along the cam profile. These points are useful to describe the movement for the CNC machine during the manufacturing of the cam.



Angle (deg)	Length (mm)
0.00	76.00
2.30	75.95
4.60	75.76
6.88	75.51
9.15	75.12
11.39	74.64
13.60	74.06
15.77	73.40
17.90	72.65
19.98	71.82
22.00	70.93
23.96	69.98
25.86	68.99
27.69	67.96
29.44	66.91
31.11	65.85
32.70	64.79
34.19	63.74
35.60	62.71
36.90	61.72
38.11	60.77
39.20	59.88
40.20	59.06
41.08	58.30
41.85	57.63
42.50	57.06
43.04	56.57
43.46	56.19
43.76	55.92
43.94	55.75
44.00	55.70



Thanks to the Adams analysis, important data was obtained to refine the stabilizer components design. Known the maximum compression value of the spring, obtained at the max steering angle, the design of the spring for the stabilizer was finalized.

CAM PARAMETERS AND EQUATIONS

Cam and Force Components

- Torque: T
- Spring Force: F_s
- Contact Force: F_c
- Axial Component: $F_{az} = \frac{F_s}{2}$
- Tangent Component: F_t
- Pressure Angle: $\alpha \quad \alpha_{max} = 68°$
- Mean Cam Diameter: $D_{CAM} = 37\ \mathrm{mm}$

Torque and Force Formulas

- $T = 2 \times (F_t \times \frac{D_{CAM}}{2}) = F_t \times D_{CAM}$
- $F_c^2 = F_{az}^2 + F_t^2 \Rightarrow F_t = F_{az} \tan\alpha = \frac{F_s}{2} \tan\alpha$

Torque Requirements

- Desired max Torque Value: $T = 20\ \mathrm{Nm}$
- $\Rightarrow F_t = \frac{T}{D_{CAM}} = 540.5\ \mathrm{N}$
- Required max Spring Force: $F_s = \frac{2F_t}{\tan\alpha_{max}} = 436.8\ \mathrm{N}$

SPRING PARAMETERS AND EQUATIONS

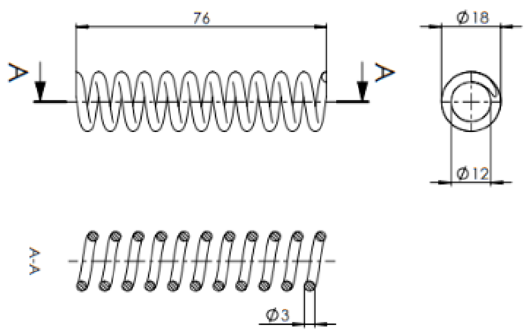
Spring Parameters and Formulas

- $F_s = K \times \Delta L$
- $K = \frac{Gd^4}{8D^3n}$
- $(G = \frac{E}{2(1+\nu)})$
- Spring Compression: $\Delta L \quad \Delta L_{max} = 20.3\ \mathrm{mm}$
- Mean Spring Diameter: $D = D_o - d = 15\ \mathrm{mm}$
- Outer Spring Diameter: $D_o = 18\ \mathrm{mm}$
- Spring Wire Diameter: $d = 3\ \mathrm{mm}$
- Number of Active Coils: n
- Shear Modulus of Rigidity: G
- G Value of Spring Steel: $G = 78\ \mathrm{GPa} = 78 \cdot 10^3 \frac{\mathrm{N}}{\mathrm{mm}^2}$
- Spring Constant: K

Calculations

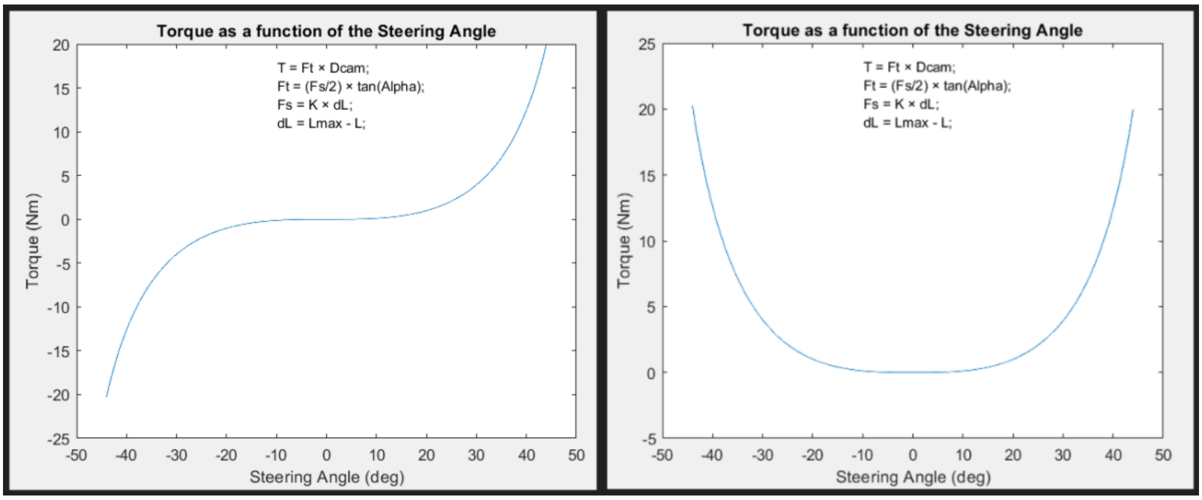
- Required Spring Constant: $K = \frac{F_s}{\Delta L_{max}} = 21.5 \frac{\mathrm{N}}{\mathrm{mm}}$
- Required Number of Active Coils: $n = \frac{Gd^4}{8D^3K} = 10.9 \approx 11\ \mathrm{coils}$

The number of active coils, the only missing parameter to fully define the spring geometry, is now known, and the spring used in the stabilizer can now be carefully selected, completely described and shown in a technical drawing.



Finally, known the compression of the spring as a function of the steering angle, it is possible to plot the value of the torque the stabilizer applies to the steering column.

The actual torque value is shown on the left diagram. The absolute value on the right.



These diagrams show that the stabilizer used as the product improvement satisfies the required objectives, by generating a low torque at the smallest steering angles, to ensure maneuverability and responsiveness during regular user actions. And producing high torque at the highest steering angles, to counteract high steering axis deflection caused by uneven terrains that suddenly turn the front wheel in an unsafe manner.

4.2 FINITE ELEMENT METHOD

In order to integrate our modification into the electric scooter, it was necessary to slightly modify the dimensions of the existing head tube. Consequently, static analyses were carried out using the Finite Element Method (FEM) and the ANSYS software.

The analysis focused on two main cases:

- Static verification of the scooter when subjected to a load equal to twice the maximum allowable load.
- Determination of the maximum velocity at which the scooter can travel in the event of a severe impact, such as a collision with a very high step, while remaining within the elastic deformation range.

CASE 1

The decision to test the scooter under twice the maximum load arises from the fact that, although prohibited by traffic regulations, the simultaneous use of the scooter by two riders is relatively common. Therefore, it is necessary to evaluate this loading condition.

For this analysis, a force of 2200 N was applied to the deck, assuming that the entire weight of the riders is supported by the deck.

The wheels were constrained to allow rotation about the z-axis, while for the rear wheel, translation along the x-axis was also permitted.

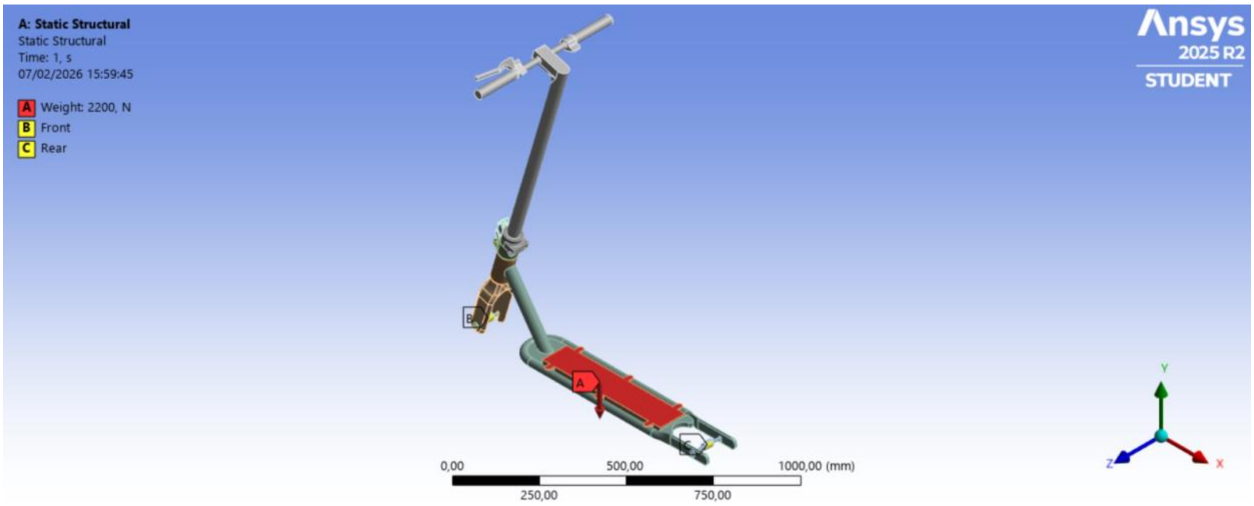


Figure 22: Forces and constraints

From the analysis, a maximum von Mises stress of

$$\sigma_{\max} = 178.51 \text{ MPa}$$

was obtained.

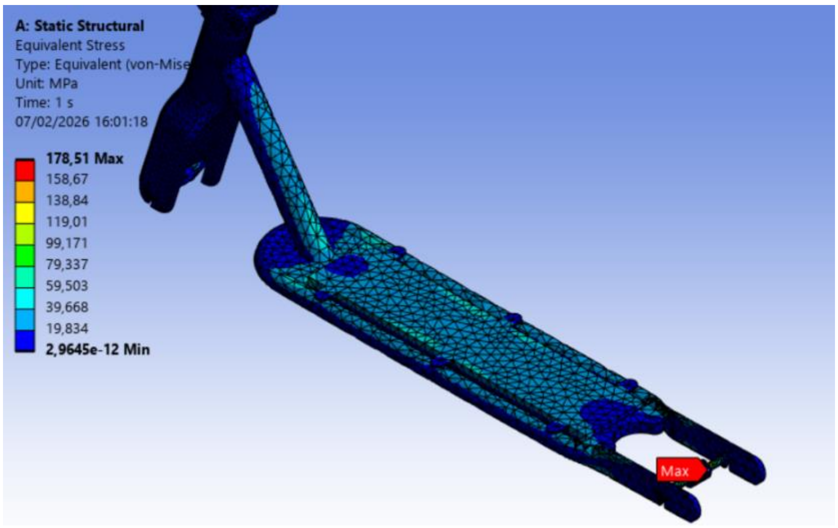


Figure 23: Equivalent stress

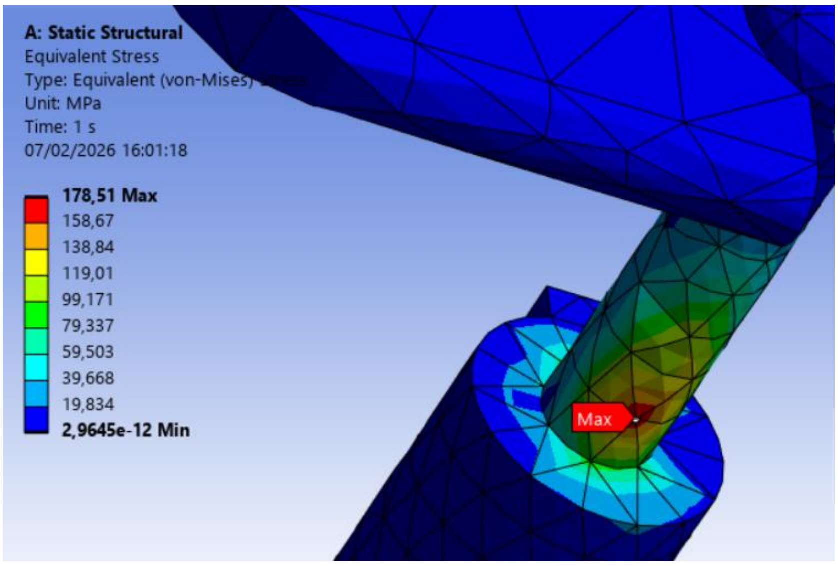


Figure 24: Equivalent stress

By selecting Aluminum 6061-T6, the ultimate tensile strength and yield strength are:

ULTIMATE TENSILE STRESS σ_u [MPa]	YIELD STRESS σ_y [MPa]
310	276

The safety factor can therefore be calculated as:

$$\eta = \frac{\sigma_y}{\sigma_{\max}} = 1.55$$

The obtained result is satisfactory, since the safety factor is greater than 1,5.

CASE 2

In this case, a single rider is assumed, and the maximum velocity that allows the scooter to remain within the elastic deformation range is evaluated.

However, additional assumptions are required:

- During the impact, the rider's weight is distributed between the handlebar and the deck. It is assumed that 30 kg of the total mass contributes to the inertia acting on the handlebar, while the remaining 80 kg acts on the deck.
- An impact duration of 0.1 s is assumed. This value represents an upper-bound estimate, justified by the damping effect of the pneumatic tire, which deforms during the impact and delays the transmission of the peak force to the rim and the frame.
  This assumption allows the dynamic peak to be smoothed, making the event compatible with a static-equivalent analysis.

In the FEM model, the rider's weight is applied to the deck, together with his inertial forces applied to both the deck and the handlebar, to obtain a condition in which:

$$\sigma_{\max} < \sigma_{sn}$$

The values used in the analysis are:

$$P = m_{\text{tot}} \cdot g = 1100 \text{ N}$$
$$F_{\text{deck}} = \frac{m_{\text{deck}} \cdot V}{\Delta t} = 1760 \text{ N}$$
$$F_{\text{handlebar, tot}} = \frac{m_{\text{handlebar}} \cdot V}{\Delta t} = 660 \text{ N}$$

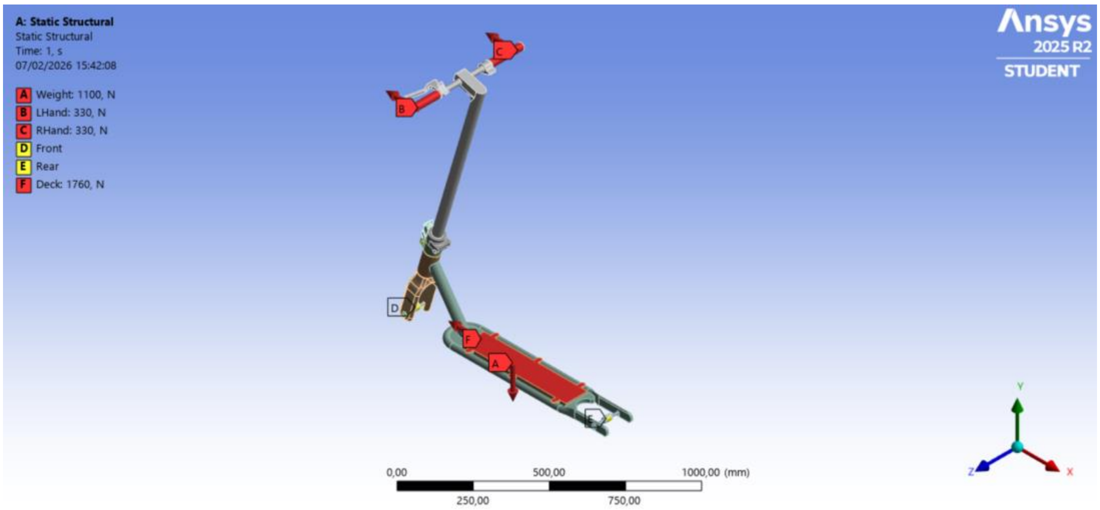


Figure 25: Forces and constraints

Using these values, a maximum stress of:

$$\sigma_{\max} = 257.43 \text{ MPa}$$

was obtained.

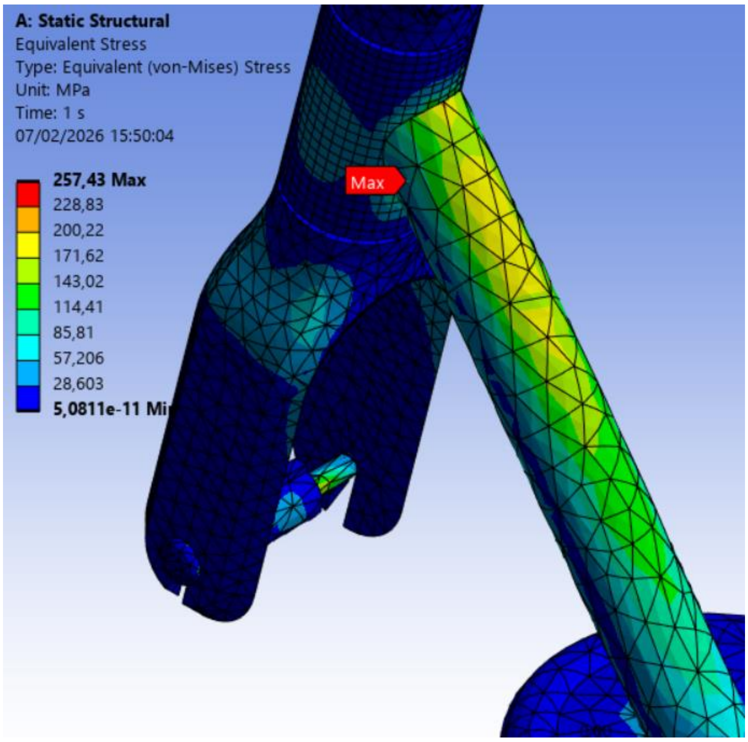


Figure 26: Equivalent stress

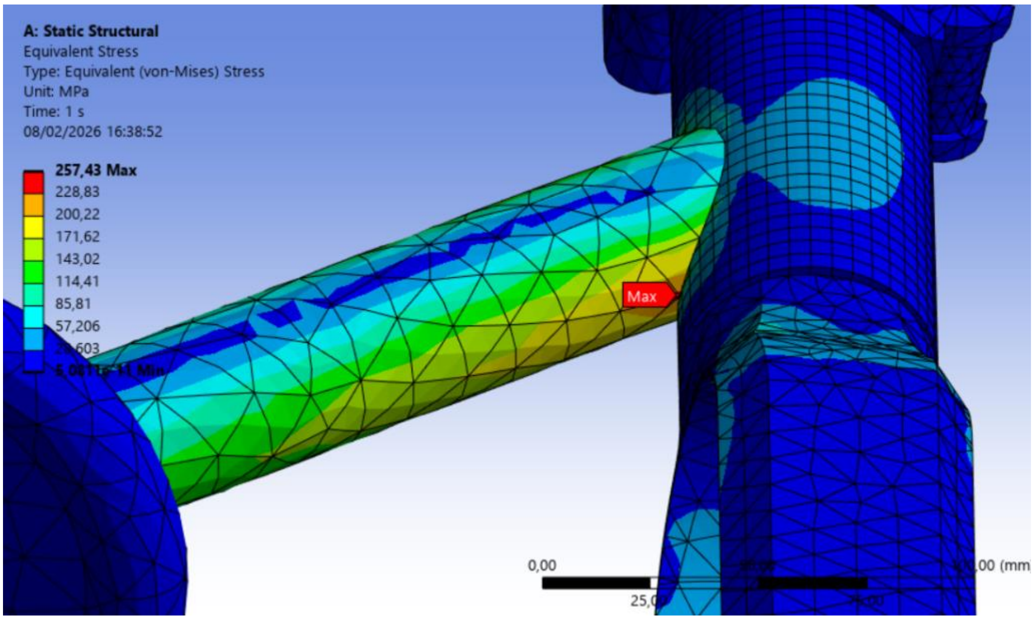


Figure 27: Equivalent stress

Therefore, using the previously described equations, the maximum allowable velocity is found to be:

$$V_{\max} = 2.23 \text{ m/s} \approx 8 \text{ km/h}$$

The modification to the head tube did not worsen the mechanical properties of the scooter. Therefore, the proposed improvement solution meets the requirements established in the previous sections.

5. MANUFACTURING PLAN

5.1 DESIGN FOR X (DFX) - STABILIZER INTEGRATION

The selected improvement is a passive mechanical steering stabilizer intended to reduce steering oscillations caused by road irregularities, while preserving the original foldability and steering range, and user ergonomics. The design was refined using a Design for X approach to ensure that the concept can be manufactured, assembled, validated, and serviced at scale within typical e-scooter cost and packaging constraints.

5.1.1 Design for Manufacturability (DFM)

The stabilizer is intentionally built from a small number of simple, process-friendly parts. Critical interfaces are limited to the steering pivot region to reduce tolerance stack-up and to keep performance stable across production lots.

Primary processes: CNC turning/milling for small metal components (shaft, axle, cam, follower, pins), stamping or laser-cut bending for brackets, and injection molding for polymer bushings/covers.

Geometry rules: avoid deep pockets and undercuts; prefer axisymmetric parts and constant-thickness brackets to minimize tool changes and enable fast cycle times.

Surface engineering: corrosion protection via anodizing (Al parts) or zinc/nickel plating (steel parts); low-friction liners to avoid wear of internal components and maintain correct contact behavior.

Tolerance strategy: specify tight tolerances only where they directly affect steering feel (bushing clearance, coaxiality). Use standard tolerances elsewhere to control cost.

5.1.2 Design for Assembly (DFA)

Assembly effort is minimized by easily joinable geometries, part with chamfers to ease insertion and by reducing the number of unique fasteners. The stabilizer should be installable without reworking the frame and without interfering with the folding mechanism.

Module concept: a compact subassembly that interfaces with the head tube/steering column using existing or minimally modified mounting points.

Fastener standardization: limit to one or two screw sizes; use prevailing-torque nuts or thread-locking features for vibration robustness.

Poka-yoke: keyed or asymmetric features prevent incorrect orientation (e.g., cam orientation), reducing assembly errors.

5.1.3 Design for Safety and Compliance (DFS)

Because the stabilizer acts directly on steering dynamics, safety is treated as a primary design driver. The stabilizing torque must not cause steering lock, unexpected return-to-center behavior, or reduced steering reactiveness.

Fail-safe requirement: in the event of wear or partial failure, performance should degrade to the baseline scooter behavior (reduced spring action), not to seizure.

Mechanical limits: preserve original steering stops and steering angle; maintain clearance to the folding hinge and locking lever throughout the fold/unfold kinematics.

Environmental sealing: protect the pivot area from dust/water ingress (simple cover, boot, or labyrinth features) to keep steering feel consistent over time.

5.1.4 Design for Reliability and Service (DfR/DfS)

The stabilizer is subjected to high-cycle excitations from pavement roughness; therefore fatigue life, wear resistance, and maintainability are required for acceptable lifetime cost.

Wear management: design metal-to-polymer or polymer-to-polymer contact pairs; make bushings or friction inserts replaceable as they deteriorate.

Inspection and service: enable access with common tools; target short service time for bushing/spring replacement without fully disassembling the steering column.

Quality control: verify functional torque range at end-of-line (simple torque test at defined steering angles) to catch over-preload or misassembly.

5.2 GEOMETRY AND INTEGRATION

The following practical guidelines translate the DfX principles into concrete CAD and integration decisions for the steering stabilizer and surrounding interfaces.

Package close to the steering axis to reduce required stabilizing torque and avoid large external appendages that increase snag risk and mass moment.

Use a single, bounded preload adjustment (with a hard stop) to avoid over-tightening that could create excessive steering stiffness.

Add generous fillets at bracket transitions and spring seats to reduce stress concentration and improve fatigue performance under vibration.

Prefer standard catalog parts (springs, fasteners, bushings/bearings) to reduce lead time, simplify sourcing, and improve field serviceability.

Avoid sharp edges and protrusions near user-contact areas; maintain clearance to cables and the folding mechanism across full steering and folding motion.

Design for contamination: integrate simple covers/shields to minimize dust and water entering the hinge area; design drainage paths where water could accumulate.

5.3 PRELIMINARY MANUFACTURING AND ASSEMBLY ROUTE

A preliminary production route is proposed to demonstrate feasibility and to define the main cost and risk drivers for industrialization.

5.3.1 Part manufacturing

Metal shaft/seat: CNC turning (and light milling if required) followed by deburring and surface treatment.

Bracket: stamped and bent sheet metal (or laser-cut + press brake for low volume prototypes) with corrosion protection coating.

Bushings/covers: injection molded polymer parts; prototype versions can be 3D printed for fit checks before tooling.

5.3.2 Assembly sequence

Install the first bearing on the fork. Insert the spring, the follower, the pin and the rollers; insert the fork in the head tube, position the cam, install the second bearing and apply thread-lock where specified.

Verify clearance to folding mechanism and cable routing, perform torque check and final safety inspection.

5.3.3 Validation checkpoints

Dimensional inspection of pivot-critical features (bushing clearance, coaxiality).

Functional torque test at end-of-line to ensure stabilizing torque is within spec.

Vibration/rough-road endurance test on a representative sample to validate fastener retention and wear stability.

6. CONCLUSION

This project presented a structured design methodology applied to the improvement of an urban electric scooter, with a specific focus on steering stability and user safety. Starting from a comprehensive analysis of market needs, user scenarios, and regulatory constraints, the *Xiaomi Electric Scooter 4* was selected as a representative case study for identifying and addressing critical performance limitations.

Through the systematic application of design tools, steering instability in urban conditions emerged as a key issue affecting user confidence and perceived safety. Several improvement strategies were evaluated, leading to the selection of a passive axial spring steering stabilizer as the most effective and compatible solution.

The proposed stabilizer was developed through a detailed embodiment design, integrated into the existing scooter architecture to preserve core attributes. Kinematic simulations confirmed that the selected cam–spring mechanism ensures responsiveness and maneuverability. Finite Element analyses demonstrated that the modified structure satisfies safety requirements.

Overall, the proposed design successfully enhances steering stability and rider confidence without compromising the original scooter concept.

7. REFERENCES

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