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An Interdisciplinary Double-Diamond Design Thinking Model for Urban Transport Product Innovation: A Design Framework for Innovation Combining Mixed Methods for Developing the Electric Microvehicle "Leonardo Project"

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Abstract: The increase in greenhouse gas emissions prompts the transport sector towards new technological perspectives on personal mobility. Addressing sustainable mobility through electric micromobility requires interdisciplinary design research methods and approaches. In the context of the LEONARDO project, funded under the Horizon 2020 framework, this paper addresses a critical literature review on the design thinking, design research models, tools, and mixed methods to be undertaken for driving product mobility innovation in a cross-disciplinary context. Following the "research through design" research strategy, the authors applied the Double-Diamond design thinking model to frame the design research process in four phases, aligning with three overarching objectives, four specific research objectives, and 24 research tasks, supported by a total of 71 mixed methods and tools. As a result, the transdisciplinary process provides a co-designed energy-efficient stand-alone microvehicle and a scalable interdisciplinary design model for urban transport product innovation. In conclusion, this case study suggests the value of the Double-Diamond design thinking model as a design research instrument capable of addressing sustainable mobility and guiding interdisciplinary design research, design practice, and education in the industrial engineering and design disciplinary sectors.

Keywords: interdisciplinary design model for urban transport product innovation; double-diamond design thinking model; interdisciplinary research methods; mixed-methods; electric microvehicle; micromobility; sustainable mobility

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1. Introduction

The increase in greenhouse gas emissions prompts the transport sector towards new technological perspectives on personal mobility [1]. In the last few years, the major strategy adopted to achieve a decrease in pollutants and the adoption of more sustainable and active mobility lifestyles is electric micromobility. This term frames light and active vehicles, human-powered and electrically assisted, that weigh up to 350 kg and can reach a maximum speed between 25 and 45 km/h [2], according to the country's regulations.

The emerging interest in these convenient and efficient alternative means of transport has led to the exploration of the role of design and engineering researchers and practitioners in cross-disciplinary contexts. This paper, therefore, shows the design research results of the research project "MicrovehicLE fOr staNd-Alone and shaReD mObility—LEONARDO", funded by the European Commission under the Horizon 2020 framework.

MicrovehicLE fOr staNd-Alone and shaReD mObility—LEONARDO

The main programme H2020 on "Societal Challenges—Smart, Green, And Integrated Transport" sets the basis for understanding the urgency of achieving citizens' mobility needs, a climate-resilient economy, and an energy-efficient low-carbon society [3]. Focusing on the call for a disruptive change in public transport, the LEONARDO project addresses the topic "Next Generation electrified vehicles for urban and suburban use", proposing a work program tackling the subtopic "Urban light personal mobility" (see [4]). In this research context, the overarching objectives of the LEONARDO project are (i) to define a new microvehicle enhancing existing micromobility technologies to foster the actual paradigm shift in urban mobility [5] through designing a climate- and environmentally friendly and safe mobility solution; (ii) to define the compatibility with sharing mobility schemes; and (iii) to perform an extensive demonstration test in a real environment in Europe for a revision and re-design process to reach the Technology Readiness Level (TRL) 8–9 [6]. Moreover, this research project aims to develop the mass diffusion of microvehicles by implementing and prototyping a fully electric urban transport product with increased autonomy. Indeed, the research team addresses the issues related to the high cost and large need for charging infrastructure, rethinking the existing sharing systems. Notably, the researchers propose a solution where the battery is shared, instead of the microvehicle, reducing the daily time-wasting charging and the city's necessity to provide spaces for recharging parking stations. Therefore, the project foresees the development of an auxiliary battery to adapt to the "Battery pack sharing, monitoring, and management system" (Priority number 102018000001810, see [7]), previously patented by the University of Florence.

This project's consortium has an efficient industrial, administrative, road safety, and consultancy background, involving (i) manufacturing companies, in charge of the prototypes' production and of the design of solutions that consider cost constraints, and (ii) research centres for identifying and collecting technical and bureaucratic product requirements. Notably, WP1 aims to critically review the literature on existing microvehicles and urban vehicles, involving research centres to gather legislative European aspects, data from accidents, and requirements on safety. WP2 has several objectives, including (i) defining and designing the final vehicle concept through the generation of detailed vehicle specifications, involving the manufacturing companies; (ii) identifying and defining mechanical design aspects, such as the exterior and functional features, materials, and structural sizing, involving the manufacturing companies; and (iii) defining electrical design and purchasing or developing elements that have to be integrated into the microvehicle, involving the manufacturing companies. Lastly, WP3 aims to develop a running microvehicle prototype, all the mechanical parts, and components, and design the assembly for field tests, involving the manufacturing companies.

The work plan of this initial research stage let the researchers identify the need for further interdisciplinary collaboration, in addition to the existing partnership, between industrial engineering and design disciplinary sectors. The engineering research team embraces the potential, opportunities, and sources of value creation this cooperation could offer. Therefore, the research team was enlarged to support the design of this attractive, affordable, resource-efficient, safe, seamless, and new micromeans of transport.

In consequence, the current contribution is strictly related to the first three work packages, aiming at developing and providing the first version of the microvehicle for on-field pilots. This renovated systemic research vision also set the basis for broadening the research horizon through the development of an "interdisciplinary design model for urban transport product innovation", enabling research scalability. Starting from this cross-disciplinary perspective, the researchers identify further specific research objectives to address in parallel and support the project's objectives, which are as follows: (i) to define a scalable and replicable design model for urban transport product innovation; (ii) to correlate mixed methods that can be used from different scientific disciplinary sectors; (iii) to highlight the hierarchical structure of the design research phases and the corresponding research tasks to be undertaken; and (iv) to evaluate the design model, developing and prototyping the "Leonardo" microvehicle. Therefore, the research questions are as follows: (i) What are the main design frameworks for innovation capable of supporting the development of new urban mobility products? (ii) Which design research tools and methods enable the urban mobility product development? (iii) Which tools and methods, specific to the industrial engineering disciplinary sector, enable product development?

This paper is organized as follows. Section 2 critically reviews the current literature on the existing frameworks for innovation. The authors are oriented by the previously highlighted research questions and address the second and third specific research objectives. The results are discussed and summed up through the definition of a graphic visualization. Then, Section 3 is about the methodological approach, the design research strategy adopted, how the research tasks have been structured into work packages (WPs), and which tools and methods have been employed. Following this, Section 4 is about the "Leonardo Project" and its developing and prototyping results. In Sections 3 and 4, the research team tackles the third and fourth specific research objectives. Lastly, Section 5 discusses the scalability and replicability of the project through the definition of the design model addressing the first specific research objectives.

2. Design Framework for Innovation

The design research team frames the design thinking approach as a user-centred and iterative driver of "innovation and creative problem-solving" [8,9], capable of defining micromobility solutions valued by testing end-users. This section provides an overview of the present "Double-diamond" design thinking framework for innovation, highlighting its hierarchy, attributes, and related tools. Therefore, the research team sets the basis for delineating the design journey and accurately structuring WPs, research tasks, and activities, starting from dividing the process into a problem and solution space.

The authors consider "design thinking" as a visionary, inspiring, disruptive, creative, and organizational model that bridges the two disciplinary sectors and fosters the expected outcomes across working groups. In recent years, many researchers extended the design domain to the engineering field, discussing the potential of "design thinking" and how it can broaden engineering skills [10]. This approach is envisioned as a problem-oriented, socially positive, and high-performance approach to foster empathy, creativity, and innovation in engineering design [11–13]. The literature also highlights how design thinking could be supportive in a communicative way, facilitating interactions within interdisciplinary and informal social team environments, and capable of achieving the complexity of the research challenges [12,14,15]. Panke [16] discussed how fruitful and effective it is to apply "design thinking" in a varied scientific field in higher education and listed the following positive traits and effects: (i) encouraging tacit experiences; (ii) increasing empathy; (iii) reducing cognitive bias; (iv) promoting playful learning; (v) creating flow/verve; (vi) fostering inter/meta-disciplinary collaboration; (vii) inducing productive failure/increasing resilience; (viii) producing surprising and delightful solutions; and (ix) nurturing creative confidence. These multifaceted features highlight the reasons for integrating design thinking in higher education among different disciplines and demonstrate the possible emerging outputs. Similarly, Micheli et al. [8] provided further insights into "design thinking" by discussing the general attributes to better understand what constitutes it: (i) creativity and innovation; (ii) user-centeredness and involvement; (iii) problem-solving; (iv) iteration and experimentation; (v) interdisciplinary collaboration; (vi) ability to visualize; (vii) gestalt view; (viii) abductive reasoning; (ix) tolerance of ambiguity and failure; (x) blending rationality and intuition; and (xi) design tools and methods. The last feature refers to strategies that can enable the other characteristics. The development of personalized, human-centred, co-creative, and innovative novel ideas is, therefore, determined by tools and methods through balancing analytical and intuitive thinking [17]; understanding relationships, environmental factors, trends, backgrounds, and user needs [18]; accepting and embracing uncertainty [19]; integrating diverse research perspectives

[20]; adopting a nonlinear, iterative, and alternative approach; and developing or prototyping visual insights.

Researchers frame tools and methods within design models and phases to better solve "wicked problems" (see [21]). The following subsection delves into the existing design thinking model and, notably, the authors explore the "Double-diamond design thinking model" in more detail.

Double-Diamond Design Thinking Model

Design philosophers, design companies, and councils have published many design thinking models since the design thinking perspective was theorized [22]. The literature presents about 15 similar models that slightly differentiate one another by addressing different challenges in varying research contexts and areas [22,23], among which the most known are as follows: (i) collective action toolkit [24]; (ii) design thinking [25]; (iii) design thinking bootleg [26]; (iv) human-centred design toolkit [27,28]; (v) the double diamond [29]; and (vi) service design [30].

The correlation between the design thinking models presented shows five clear correspondences and Kueh and Thom [22] framed them into the following phases: (i) the context or problem framing phase; (ii) the idea generation phase; (iii) the prototyping phase; (iv) the implementation phase; (v) and the reframing phase. These similarities enable every model to approach the research challenges. Notably, the authors explore the Double Diamond as the model visually capable of highlighting divergent and convergent thinking in the design process.

The straightforward Double-Diamond design thinking process, originally developed by the British Design Council [29], foresees four consequential, explorative (divergent), and exploitative (convergent) key phases: (i) discover; (ii) define; (iii) develop; and (iv) deliver [31].

The "Discover" and "Define" phases refer to the "Context or problem framing phase". The "Develop" phase refers to the "idea generation" phase. The "Deliver" phase refers to the "Prototyping" and "Implementation" phases.

In the first diamond, the "Discover" divergent phase is about "broadening our horizons" through research. This is the inspiring fuzzy starting point on the topic, the products or services constraints, and the related complex problems users are facing. The aim is to understand the context of the problem, identify the macro-trends and the related technological advancements, empathize, and engage whoever is affected by the issues of the research to perceive the end-user perspective, motivations, and latent needs and uncover disruptive ideas. Moreover, the literature provides much research on which tools and methods it could entail [8,16,32–37]: (i) systematic literature review; (ii) secondary research; (iii) case study research; (iv) ethnographic design methods; (v) identify stakeholder; (vi) interview; (vii) survey; (viii) questionnaires; (ix) card sorting; (x) field study; (xi) user observation; (xii) user shadowing; (xiii) empathy maps; (ixv) focus group; (xv) hierarchical task analysis; (xvi) benchmarking (see Figure 1).

The "Define" convergent phase is about "heading towards the core problem" and actionable tasks. This is a reflective phase regarding the previously collected knowledge resource and design insights. The aim is to analyze, synthesize, co-design insights, and organize the input that emerged from the "Discover" phase to define the strategic brief, a technical document reporting systematically the findings into opportunities and objectives [38]. Going on, as the literature stated [8,16,32–37], it could entail the following tools and methods: (i) thematic analysis (see [39]); (ii) content analysis (see [40]); (iii) personas; (iv) stakeholder analysis; (v) stakeholder map; (vi) task mapping; (vii) experience map; (viii) scenarios of use; (ix) user journey map; (x) service blueprint map; (xi) affinity mapping; (xii) mind maps; (xiii) miro.com (see [41]); (ixv) SWOT analysis; (xv) Kano model; (xvi) brainstorming; (xvii) "How might we" question; (xviii) focus group; (xix) co-design workshop; (xx) design brief (see Figure 1).

In the second diamond, the "Develop" divergent phase is about "co-expressing and developing disruptive ideas in a free-thinking environment". This is a collaborative design phase of the strategic brief. The aim is to generate an iterative co-dialogue with involved stakeholders, researchers, designers, and experts on the data gathered to design the outcome's desirability, feasibility, and viability. Moving forward, as the literature stated [8,16,32–37], it entails the following tools and methods: (i) brainstorming; (ii) "How might we" question; (iii) focus group; (iv) co-design workshops; (v) mind maps; (vi) miro.com; (vii) concept maps; (viii) design guidelines and standards; (ix) sketching; (x) crazy eights; (xi) design-by-drawing method; (xii) sprint and design sprint (see [42–44]); (xiii) storyboard; (ixv) visual storytelling; (xv) scenario building; (xvi) AI assistive tools (see Figure 1).

The "Deliver" convergent phase is about "transforming insights into real outputs". This is about prototyping and testing promising emerging insights. The aim is to enable the designers to explore the idea selected, whether in low or high fidelity, select valuable ones, and receive feedback about the users' perception, usability, affordance, or accessibility of the outcome. Lastly, as the literature stated [8,16,32–37], it entails the following tools and methods: (i) storyboard; (ii) LEGO Serious Play (see [45]); (iii) scenario building; (iv) 3D modelling with parametric software (e.g., Fusion [46] or SolidWorks [47]); (v) rendering software using Keyshot [48] or Lumion [49]; (vi) wireframes using AutoCAD or Adobe Illustrator; (vii) virtual prototyping (e.g., Meta Quest); (viii) AI assistive tools; (ix) physical prototype; (x) mock-ups; (xi) rapid prototyping; (xii) 3D printing; (xiii) field experiments; (ixv) usability testing; (xv) user testing; (xvi) A/B test (see Figure 1).

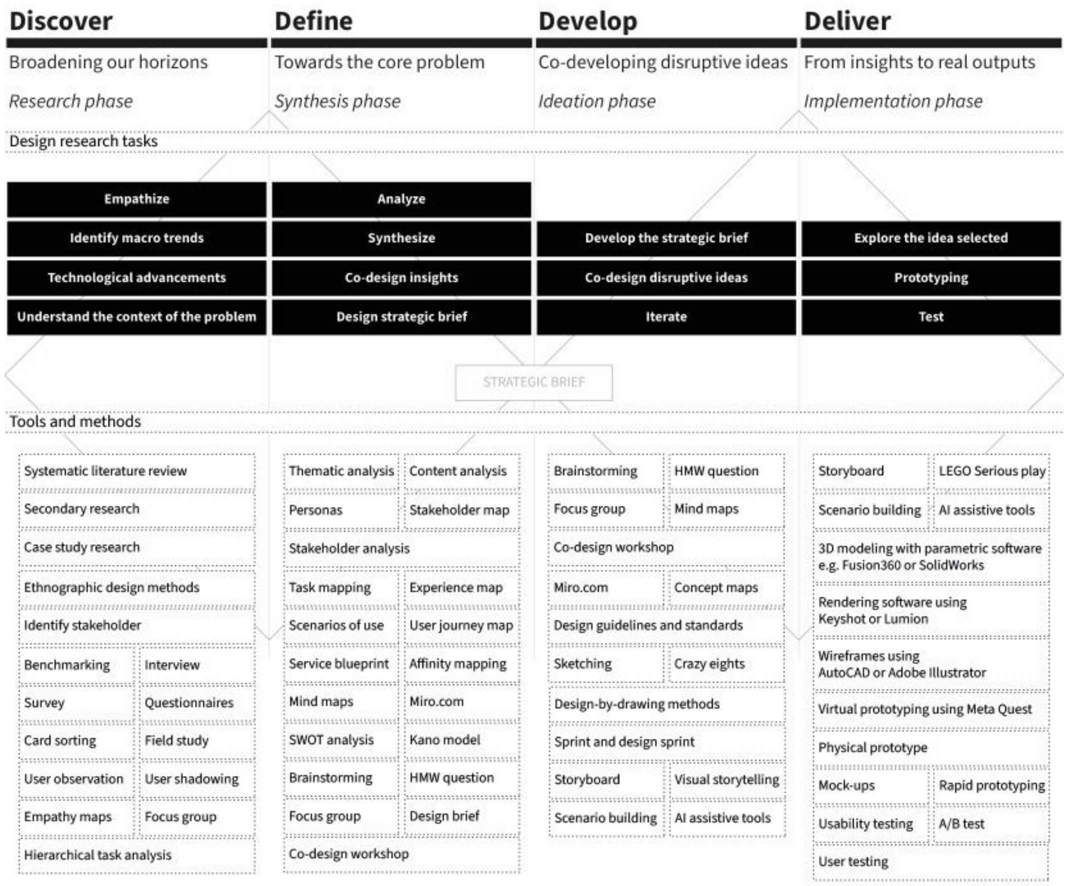

Figure 1. Design Framework for Innovation. The figure adopts the "Double-diamond design thinking model" [29] to summarize the results from the critical literature review.

In conclusion, the present section sets the basis for framing the methodological approach of the research project "Leonardo" through a critical literature review of the

"Design thinking" attributes, process, models, phases, and tools. The authors, therefore, identified the "Design thinking" process as a framework for innovation and organized the research through the "Double diamond design thinking model".

3. Materials and Methods

The research strategy adopted is "research through design" (see [50]) and aims to produce knowledge to guide interdisciplinary design research, practice, and education in defining urban transport product innovation.

The Design Framework for Innovation, framed in Figure 1, is used as an interdisciplinary design research model for organizing data gathered from the initial brief, structuring the research phases, selecting specific mixed methods, developing research materials, and designing research activities. This model enables the research team to understand the context, opportunities, and insights to explore formal, technological, and functional microvehicle innovation ideas and define a scalable interdisciplinary design model for urban transport product innovation. Notably, the model was used for organizing the research design process in 4 WPs, aligning with 3 specific research objectives for each research direction and encompassing 14 research macro-tasks and 24 corresponding micro-tasks. The research tasks were addressed by employing quantitative and qualitative research methods from different disciplinary sectors.

3.1. WP1: Discover Phase

During the initial "Discover" phase, the team organized the research phase into 4 macro-tasks, presented in Figure 1: (i) identify macro-trends; (ii) understand the context of the problem; (iii) empathize; and (iv) conduct in-depth analysis of the technological advancements.

The first macro-task was addressed by the design research team and aimed at deepening analysis of the topic proposed, which is the research project "LEONARDO". The engineering research team presented their initial brief, the challenges, the research objectives, the expected outcomes, and the deadlines. Thus, the design research team employed the critical literature review and case study research methods to delve into the mobility field and electric micromobility strategy to quickly achieve sustainable goals.

The second macro-task is about understanding the context of the research project and the research team organized the work into the following micro-research tasks: (i) an in-depth analysis of the brief; (ii) an in-depth analysis of the project partners; (iii) an in-depth analysis of the disruptive micromobility product to define; (iv) the mapping of the research areas; and (v) the framing of the research methods. Firstly, the research team re-analyzed the project priorities and constraints, included in the Grant Agreement. Going on, they designed the first participatory activities, with the principal investigator, project experts, research partners, partner company, and design and engineering researchers, through the use of focus groups and semi-structured interviews to identify the corresponding stakeholders and relevant implicit factors. The research team also made comparable benchmarks of the kick scooters and monowheels as product-related market segments. The aim was to analyze the competitors, similar to the blended microvehicle proposed by the research project, and identify formal emerging trends, technological advancements, manufacturing processes adopted, materials employed, user needs, and user evaluations. Finally, brainstorming and workshops with the principal investigator, project experts, and design and engineering researchers were organized to map the research areas and directions to follow for defining the expected outcomes. The research team also framed the research methods into a graphic visualization that was highly iterated during the process and reported in Section 5.

Moving forward, the third macro-research task is about empathizing with the users and performing (i) an in-depth analysis of the stakeholders and (ii) the user interactions. The research team adopted ethnographic design methods from the design research literature review and used semi-structured interviews, hierarchical task analysis, user shadowing, and user observation tools to identify how users interact with kick scooters and monowheels. These qualitative methods set the basis for identifying new design insights regarding the positioning of the feet and the need to delve into anthropometric data. Particularly, the research team sized the components according to the anthropometric parameters for the European population (see [51]).

Lastly, the research team analyzed technological advancements through secondary research. Some previous tasks were iterated, involving creating benchmarks and performing critical academic literature reviews and case study research on materials and manufacturing processes adopted by companies in the mobility sector. The researchers also delved into patent research and technical literature reviews through comfort, mechanical strength, safety, and rigidity regulations to examine which materials could fulfil the project requirements fully. The team deepened the analysis of safety regulations, requirements, and framework conditions to let these vehicles circulate on public roads through accident databases and international literature. Going on, they address the safety analysis through (i) investigation of kick scooter-related regulations in European countries; (ii) mapping of kick scooter accidents in Germany; and (iii) a survey on the use of kick scooters. They addressed legal and technical frameworks and municipal regulations of the microvehicles through accident analysis. The latter investigation was carried out through the analysis and mapping of the (i) conflict and collision situations and constellations; (ii) data information on personal injuries; and (iii) related accident parameters regarding the location and the use of helmets and protective clothing.

3.2. WP2: Define Phase

The "Define" phase was about synthesizing the data collected in the previous stage of development. The team structured the work package into 4 macro-tasks, as presented in Figure 1: (i) analyze the data gathered; (ii) synthesize data; (iii) co-design insights; and (iv) design a strategic brief into a technical document. The first macro-task aimed to deepen the data collected through the use of thematic analysis and content analysis in a participative environment, with the principal investigator, project experts, and design and engineering researchers. Going on, the research team synthesized the knowledge resources through the use of SWOT analysis, brainstorming, and participatory affinity mapping. Coherently, they defined an overview of the product components framing the entire assembly through a task mapping tool to identify the main elements and the research directions that need to be focused on during the "Develop" and "Deliver" work packages. After defining the strengths, opportunities, weaknesses, and threats, the third macro-task fostered co-design activities through brainstorming, focus groups, and co-design workshops to define insights. Lastly, the team organized the work through (i) opportunity areas mapping and (ii) defining the correct research question to orient the second diamond. These two micro-tasks were supported by affinity mapping, HMW questions, and brainstorming tools in a co-design context to design the strategic brief.

3.3. WP3: Develop Phase

The third diverging phase aimed to develop disruptive and innovative ideas in a participatory context. This stage of development is organized as follows: (i) developing the strategic brief; (ii) co-designing disruptive ideas; and (iii) iterating the results that emerged from the previous macro-tasks. Initially, the research team structured the latter two work packages framing the research methods to be employed. HMW questions and a focus group with the principal investigator, the project experts, and design and engineering researchers oriented the following research phases, organizing and structuring the subsequent research tasks. Moving forward, the next research activity aimed to explore new formal solutions. The technological advancements, materials, and manufacturing processes identified in the strategic brief guided this formal exploration, and the researchers employed both design-by-drawing and design sprint methods, and the crazy eight, sketching, and visual storytelling tools. The research team organized and designed a "1-

day" design sprint (see [44]), incorporating all the tools cited in the previous paragraph. The design sprint adapted foresees the following phases, tools, and methods: (i) the idea generation through the definition of disruptive and individual HMW questions in 10 min; (ii) the sharing of the HMW questions generated and the categorization in theme through the use of affinity diagram tool in 20 min; (iii) the voting of the most coherent, compelling and important HMW question, that could orient the next research phases in 5 min; (iv) the individual fast sketching exercise through crazy eight tools in 8 min; (v) the sharing and voting of the emerged ideas and sketches in 20 min; (vi) the re-elaboration of the selected sketch in 20 min; (vii) the definition of storyboard and storytelling about how the user should interact with the final product through the use of rendering, 3D modelling, and wireframes software in 40 min; and (viii) a brief presentation of the output in 30 min. In the end, the team iterated the previous tasks as long as they identified a coherent idea.

3.4. WP4: Deliver Phase

The fourth converging phase involved the exploration and successive implementation of the selected idea. The team organized this work package into 3 macro-tasks, as presented in Figure 1: (i) exploring the selected idea; (ii) product prototyping; and (iii) product testing. As already carried out in the previous stage, the researchers iterated the framing of the research methods through HMW questions and focus groups. The second macro-task aimed at prototyping the idea selected. The team divided the tasks into three different approaches: (i) prototyping in a virtual environment; (ii) rapid prototyping; and (iii) physical prototyping. Firstly, the team explored the product output through wireframes and 3D modelling with AutoCAD and the parametric software Solidworks. Subsequently, they explained how the users have to interact with the product through renderings, storyboards, and visual storytelling, defined with Lumion [49], Adobe Illustrator [52], and Photoshop [53]. The last macro-task is about testing and was structured in parallel with the prototyping one as follows: (i) remote quantitative testing and (ii) testing following regulations. Before possibly testing the product in person, the research team performed a usability test with Google Forms. The objective was to understand how attractive, perspicuous, efficient, dependable, stimulative, and innovative the product appears to be. Therefore, the team grouped 27 people to which they presented the Leonardo microvehicle and submitted a questionnaire, asking the following questions: (i) "An overall impression of the product. Do users like or dislike it?"; (ii) "Is it easy to get familiar with the product and learn how to use it?"; (iii) "Can users solve their tasks without unnecessary effort? Does it react fast?"; (iv) "Does the user feel in control of the interaction? Is it secure and predictable?"; (v) "Is it exciting and motivating to use the product? Is it fun to use?"; and (vi) "Is the design of the product creative? Does it catch the interest of users?". The researchers identified the Likert scale as a coherent question type to express the level of agreement or disagreement in the samples and quantitatively analyze the responses.

The first tangible prototypes were singular components of the assembly and were created through additive manufacturing for performing preliminary testing. Later, the research team developed different types of component prototypes for each research direction to be re-assembled into one product prototype, in collaboration with the partner company. Following regulations, the aim was to test safety, comfort, mechanical strengths, and rigidity of the materials identified in the research phase [54].

4. Results

As discussed in the Section 1, the overarching research objectives are as follows: (i) developing a new silent, clean, energy-efficient, and safe microvehicle; (ii) developing a microvehicle compatible with sharing mobility schemes; and (iii) performing an extensive demonstration (see [55]). Notably, the "LEONARDO" research project aims to enhance the features of monowheel and scooter concepts for defining a blended stand-alone microvehicle that is attractive and affordable to a wider market segment. Going on, the project foresees the design of an auxiliary battery as a touchpoint of the "battery-sharing mode" sharing system, patented and developed by the University of Florence, enhancing the project's aim to make the novel microvehicle compatible with sharing mobility schemes. Lastly, the project's expected outcomes strive to test a fleet of microvehicles in a real environment in five European cities, including Rome, Palermo, and Bruxelles.

4.1. "Discover Phase": Towards Urban Transport Product Innovation

The first "Discover" phase delves into the main objectives and research challenges. The first three macro-tasks—identifying macrotrends, understanding the context of the problem, and empathizing—set the basis for identifying that the novel microvehicle solution fosters the last mile concept and intermodal issues. In order to address these macrotrends, the design research team clusters the following product scopes: (i) increasing driving stability, ease of driving, ride comfort, and braking ability designing a highly specialized vehicle; (ii) guaranteeing flexibility through the design of a stand-alone and sharing mode; (iii) designing lightness and compactness through materials; (iv) supporting inclusivity in use, suitability, and safety; (v) reducing the dimension-weight and setting a target at 10 kg; (vi) increasing the ease of transport through the design of foldable mechanisms, trolley mode, or self-balancing; (vii) allowing the compatibility with shared mobility scheme, or rather a battery sharing, through the design of an auxiliary battery; and (vii) lowering the cost of sale and the related costs of maintenance. Starting from these product design criteria, the design research team gathers the data collected and designs a participatory workshop, focus groups, and semi-structured interviews involving the principal investigator, project experts, research partners, partner company, and design and engineering researchers. Therefore, the researchers empathize with the corresponding stakeholders, identifying their aim to achieve the initial overarching objectives, working on a hybrid vehicle conceptualized within the engineering research team (see Figure 2). According to this concept, the specific purposes are to design (i) a hub motor with a 14–16″ diameter front wheel; (ii) an easy handling, tilting, flexible, and high resistance platform; (iii) a steering system on the hub motor, lowering the weight; (iv) a high-efficient, easy-balancing handlebar; (v) a clean, minimal, and attractive geometry; (vi) an on-board battery; and (vii) an auxiliary battery, as an assembly component that makes the microvehicle compatible with shared mobility schemes.

This initial in-depth analysis of the macrotrend, brief, topic, stakeholders, and user interactions set the basis for dividing the design research process into four main research directions to simultaneously address the following factors: (i) platform designing; (ii) steering column designing; (iii) auxiliary and fixed battery case designing; and (iv) assembly designing. According to the specific project purposes, as previously outlined, the research team has to address the following factors and priorities for every research direction: (i) costs; (ii) lightness; (iii) compactness; and (iv) ease of transport.

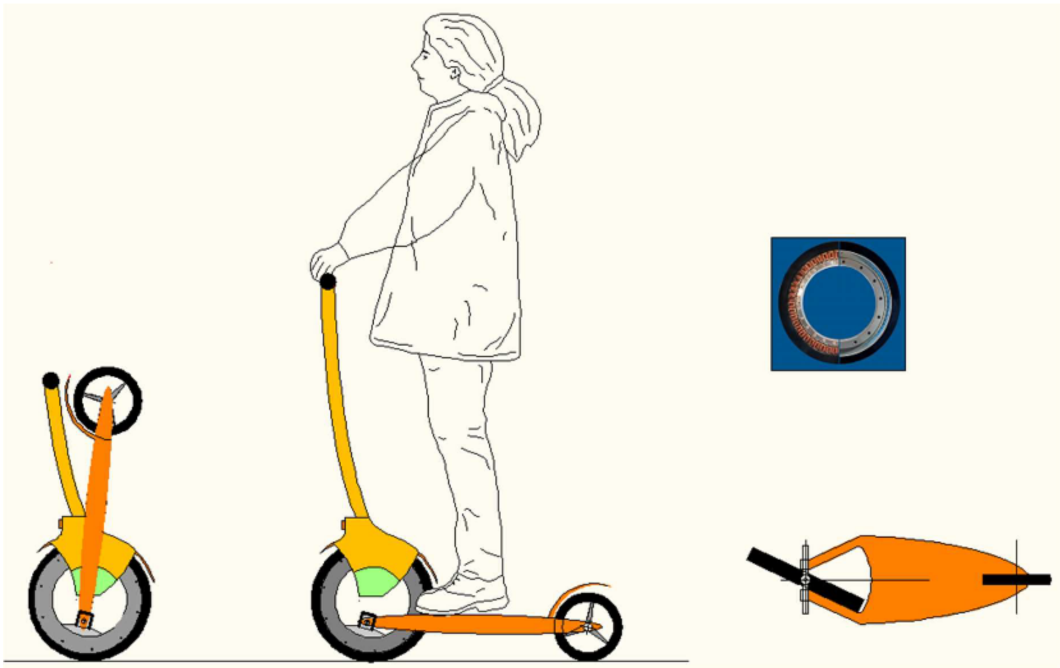

Figure 2. Microvehicle concept conceptualized by the engineering research team for the LEONARDO project (GA 101006687, see [56]).

During the development of the fourth microtask, the design research team mainly adopted the "Micromobility Landscape" (see [57]) to collect the technological advancements and implement the technical requirements for the microvehicle. In the following sub-sections, the research team presents in detail every aspect of the final work performed, dividing each one into three parts.

The first one outlines the strategic design brief of the corresponding research direction, including the collection of all information relating to technical/functional requirements and project constraints useful for defining the needs and problems that the product intends to solve. This is the result of the second "Define" phase, which synthesized the data gathered and analyzed in a participatory context.

The second one shows the results that emerged from the "Develop" phase. Notably, this paper presents the embodiment and detailed design, where the set of elaborated ideas is structured. The layouts and the preliminary drawings of the various components are visually depicted and the considerations made on the production processes are listed in technical-economic terms.

Lastly, the authors present the "Deliver" phase results, merging every research direction's prototype design and various tangible outputs in Section 4.4. The authors show the overall result of the "implementation" phase to provide an overview of the assembly.

4.2. Research Direction #1: Platform Designing

4.2.1. "Define Phase" Results: Platform Strategic Design Brief

The benchmark lets us compare similar products available on the market, such as kick scooters and monowheels. This method lays the foreground for defining four specific platform objectives: (i) providing flexibility to the platform, replacing the suspensions of traditional microvehicles for increased lightness; (ii) minimizing the weight of the entire vehicle; (iii) improving the user comfort; and (iv) supporting the "trolley mode", or rather, the ease of transport when the microvehicle is folded so that the platform does not collide with any other part in the folding process.

The first specific research objective refers to the assessment of the materials to be employed, among which the research team identifies (i) aluminum sheets; (ii) fibre-reinforced composites; and (iii) bamboo.

The second research objective refers to the ergonomic design of the platform. The researchers, therefore, identify that the minimum width of the platform in correspondence with the hinge is 190 mm. This measure is based on the front wheel encumbering and kinematics, consisting, respectively, of a 14-inch diameter and a total steering angle of 50 degrees. Starting from these dimensions, the research team defines the minimum width of the overall platform profile, which is 250 mm (Figures 3 and 4). Notably, the research team focuses their output on one relevant platform constraint: to be jointed to the front wheel and hinged a few centimetres below the centre of the wheel. The highlighted characteristic showed the platform should be wider than those commercially available and the ideal rotation angle for adequate maneuverability and driving comfort has to be set to a value of 25 degrees in both directions.

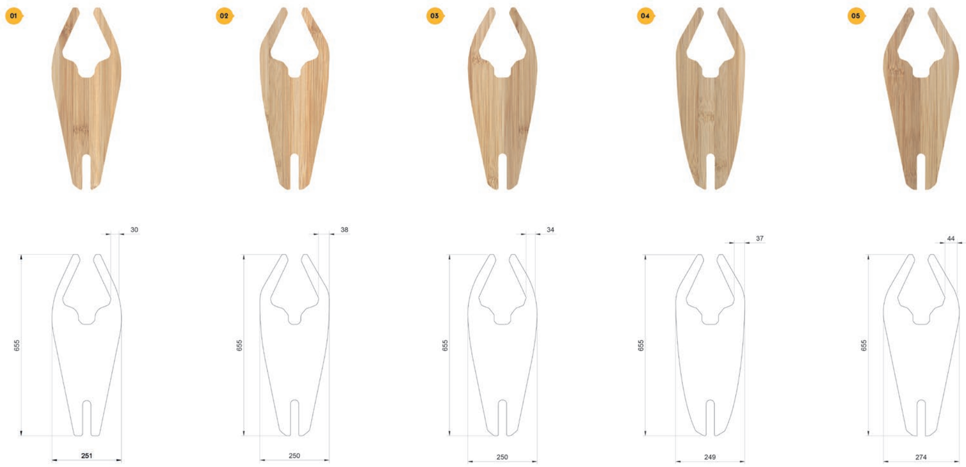

Figure 3. Five different concepts for the platform in terms of encumbering and shape. The research team chose the second concept (see Figure 4).

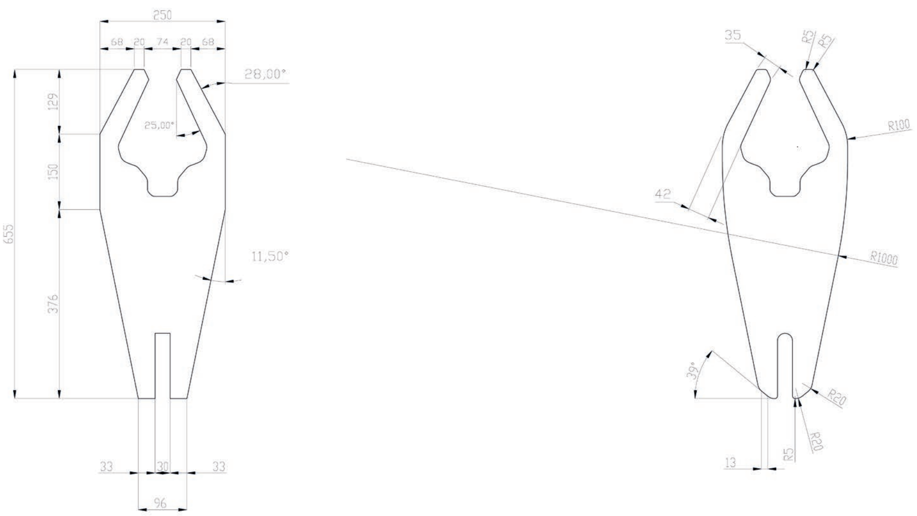

Figure 4. Final selected geometry and encumbering of the LEONARDO platform.

4.2.2. "Develop Phase" Results: Platform Embodiment and Detailed Design

The discussion on the "Design strategic brief" of the platform, presented in Section 4.2.1, is addressed and brainstormed by the research team through a focus group with all the experts on the project.

Starting from the anthropometric data collected, the authors set the basis for identifying a new design idea: users can stand on the platform by placing their feet next to each other. This foot position enhances comfort and allows the assumption of an upright, stable, and natural position compared to typical kick scooters, in which the platform size obliges the placement of the feet one in front of the other.

Therefore, the research team focuses on a renovated formal exploration through the design sprint method, brainstorming, HMW question, crazy eight, design-by-drawing method through AutoCAD [58] and Adobe Illustrator [52], etc. They drew inspiration from the lines of the automotive sector and developed the first fast sketch aiming at conveying dynamism, innovativeness, and propensity to the future to capture the attention of the public and define the image of the product. The selected details are inserted in each acute and protruding intersection point, respecting the symmetry and balancing the proportions.

Regarding the selection of materials and processes, the research team examines three light and structurally valid solution possibilities, including (i) a sandwich of fibreglass with a PVC core with inserts of wood at the height of the hinges; (ii) layers of bamboo, with diverse thicknesses, glued together with epoxy, with lower aluminum support; and (iii) aluminum sheets of minimum thickness with aluminum ribs. These three possible alternatives are conceptualized, physically prototyped, and tested in order to be inserted inside the overall LEONARDO vehicle model. The best solution to adopt is highly iterated and identified following the mechanical evaluations (see [48]), considering the partner company's manufacturing availability, as well as through focus groups, brainstorming, and co-design workshops within the interdisciplinary research team.

4.3. Research Direction #2: Steering Column Designing

4.3.1. "Define Phase" Results: Steering Column Strategic Design Brief

The main objectives are the development of unmovable and auxiliary battery packs, to increase the microvehicle's autonomy. According to these, the research team defines four specific steering column objectives strictly related to the battery packs: (i) enhancing the ease of use; (ii) widening the volume and size of the steering column to insert the auxiliary battery in its profile; (iii) minimizing the weight through the assessment of materials and formal exploration; and (iv) supporting the "trolley mode".

The first research objective is to improve the users' comfort. Therefore, the research team decides to position the auxiliary battery inside the steering column higher to facilitate assembly and disassembly.

The second objective is about dimensioning. Starting from the collection of standard height measures, commercially agreed, the research team dimensions the height of the steering column, extending by 1000 mm, concerning the platform level.

Going on, the weight objective regards the assessment of materials and manufacturing solutions for large-scale production, among which the research team identifies (i) polyurethane and aluminum core co-moulding; (ii) plastic injection moulding; (iii) aluminum calendaring; or (iv) laser cutting and welding.

Lastly, the research phase highlights that the hub is the only stable point on which the column can be fixed, capable of supporting the "trolley mode" development. Therefore, the research team highlights the following requirements: designing (i) the folding mechanisms, coupling the platform and the column; (ii) the space, or rather a hole, along the column for positioning appropriately the rear wheel; and (iii) compactness, making sure that the final output does not impact the overall aesthetics.

4.3.2. "Develop Phase" Results: Steering Column Embodiment and Detailed Design

The "Design strategic brief" of the steering column, presented in Section 4.3.1, is brainstormed by the researchers through a focus group and HMW questions to determine which research methods are employed.

These measures set the basis to start the "co-design disruptive ideas" research task. The research team explores the form through design sprint methods, fast sketching, design-by-drawing methods, and iteration, setting the basis for the following design insights: (i) design a steering column that provides enough space for fitting the auxiliary and interchangeable battery case; (ii) design a slot at half the height of the column to accommodate the rear wheel inside the steering column profile and compact the folded position of the system while minimizing the overall volume; and (iii) shape and conform the aesthetic details, explored in the first research direction, into every designed component.

Therefore, an aesthetic recognizable visual element is created between the platform and the steering column through the use of the parametric software Solidworks and the fillet and chamfer function on the edges. This recognizable and harmonious geometry is adapted to every specific characteristic of the product.

The formal exploration research task leads to the development of an innovative, minimal, dynamic concept, whose curvature invites movement and maintains a homogeneous profile, which aligns with the shape of the platform and the other components. These concepts are displayed and illustrated in Figure 5.

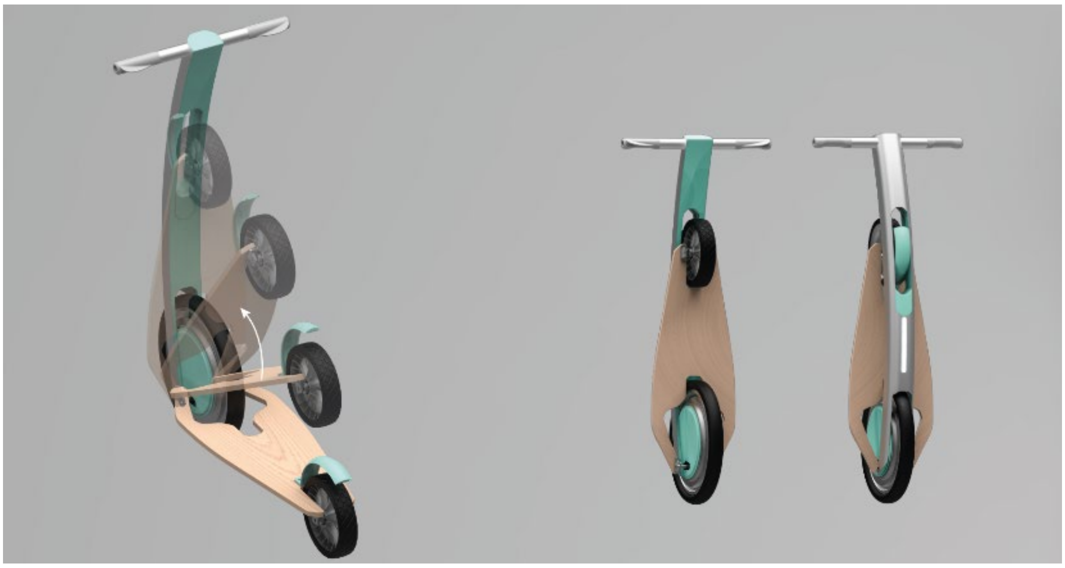

Figure 5. Possible movement of the platform concerning the steering column and front/rear view of the vehicle in "trolley mode".

Going on, the aesthetics of the column profile section is designed to be easily reproducible with low-cost technological processes, established within the panorama of manufacturers operating in Europe. Starting from these assumptions, three possible implementation solutions are formally and materially analyzed. The first involves the use of polyurethane, inside which an aluminum core is co-moulded, and consists of eight components welded together (Figure 6). The second involves the use of reinforced nylon through the injection moulding process (Figures 7 and 8). The last involves the creation of a customized extruded aluminum profile, the calendaring of the piece according to the radius of curvature considered, and laser cutting to form the central slot, the lower holes for bolts, and the housing slot for the auxiliary battery (Figure 9). In conclusion, the research team identifies the aluminum solution as the cheapest and the polyurethane alternative as the most appealing choice from an aesthetic standpoint.

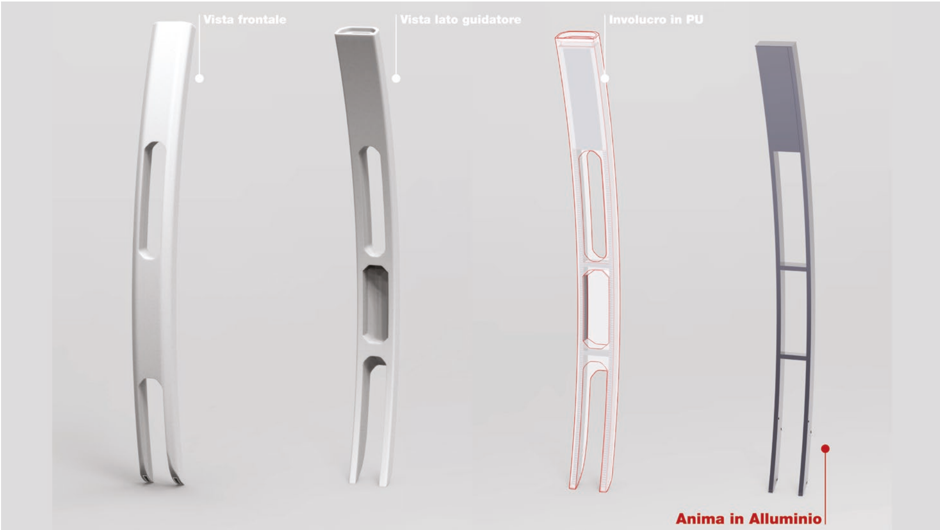

Figure 6. The concept for polyurethane and aluminum core co-moulding of the steering column.

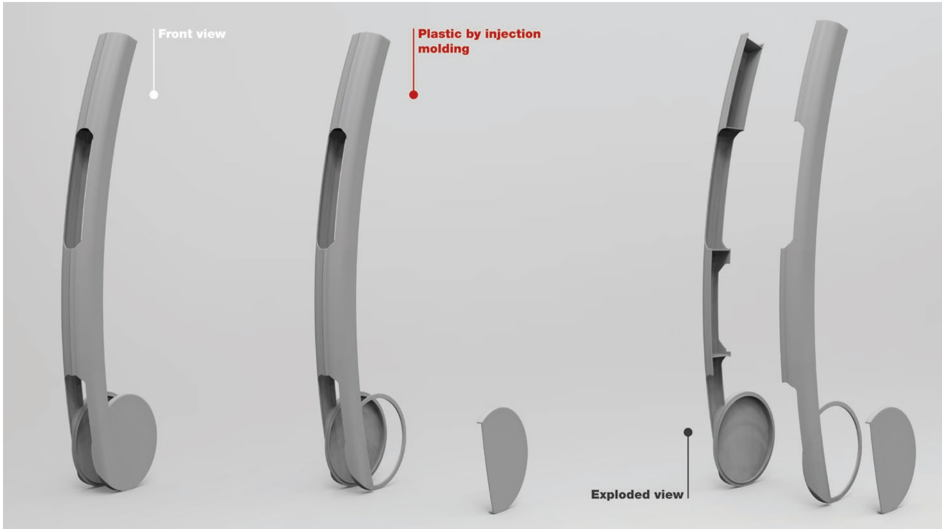

Figure 7. The concept for plastic injection moulding of the steering column.

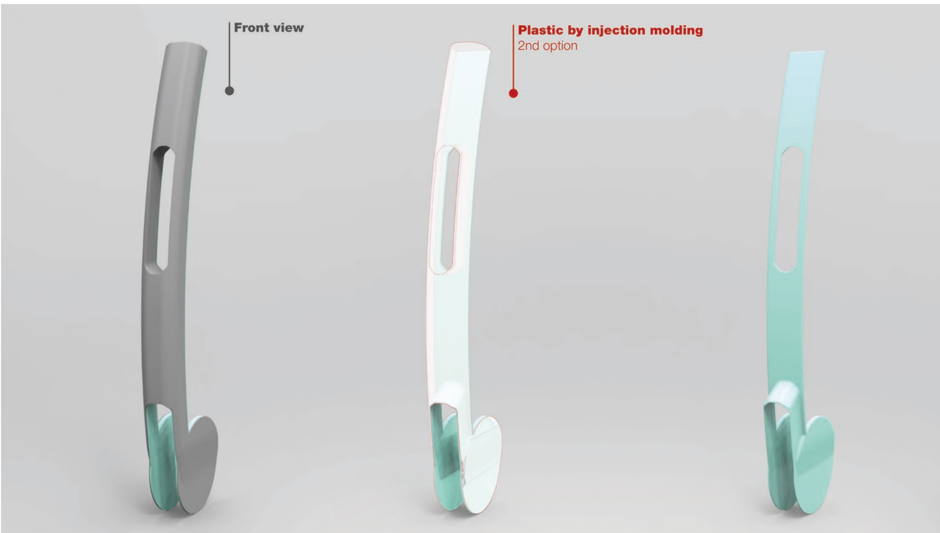

Figure 8. The concept for plastic injection moulding of the steering column (2nd option).

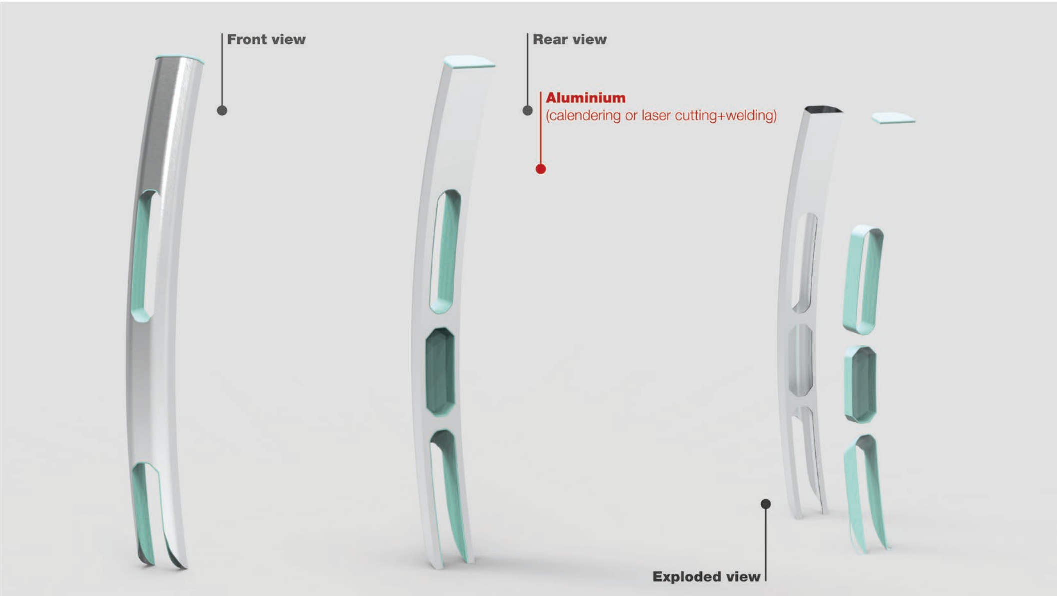

Figure 9. The concept for aluminum calendaring or laser cutting and welding of the steering column.

4.4. Research Direction #3: Auxiliary and Fixed Battery Case Designing

4.4.1. "Define Phase" Results: Auxiliary and Fixed Battery Case Strategic Design Brief

Starting from the map of the research opportunities areas, the research team frames the need to (i) dimension the auxiliary battery case and design the slot on the steering column, and (ii) dimension the fixed battery and measure the storage on the hub. The researchers define four specific auxiliary and fixed battery case objectives related to the following factors: (i) lowering the costs of the materials employed; (ii) increasing the user comfort in inserting the case in the storage; (ii) improving the compactness of the case profile to support the "trolley mode"; and (iv) increasing the ease of transport.

The design of the battery case depends on (i) the total volume occupied by the cells; (ii) the BMS; (iii) the connectors; and (iv) the adoption of the formal, recognizable, aesthetic characteristics determined in the previous subsections.

Lastly, the research team identifies the following constraints: (i) the auxiliary battery needs at least 10 batteries that measure 18.5 × 69 mm each; (ii) the fixed one needs at least 20 batteries that measure 18.5 × 69 mm each; (ii) the BMS measurements are 69 × 56 × 15 mm; and (iii) the connector is 23.85 × 8.6 × 7 mm.

4.4.2. "Develop Phase" Results: Auxiliary and Fixed Battery Case Embodiment and Detailed Design

The "Design strategic brief" of the auxiliary and fixed battery case, presented in Section 4.4.1, is brainstormed by the researchers through a focus group and HMW questions to determine which research methods are employed.

In preliminary dimensioning, the team explores the possible alternative configurations of the main auxiliary and fixed battery components, as shown in Figures 10 and 11. This sets the basis for pointing out that the steering column does not have sufficient space to insert a case containing more than 10 batteries. Therefore, the research team starts exploring the initial concepts by using graphical two/three-dimensional tools to better represent the inscribed auxiliary battery case. The peculiarity of the idea selected is the upper part of the case side profile, which describes the arc of a circle. The team designs this detail to foster ease of use in performing the downward movement for inserting the case and improving the user–product interaction. As depicted in Figures 12 and 13, its centre coincides with the lower end of the case housing inside the steering column. This point is identified as the case's pivot for insertion. The 3D models, of both the auxiliary and fixed battery case, are designed to prototype a preliminary 3D printing model. Additionally, the team selects the reinforced nylon and the injection moulding process as a manufacturing process. Therefore, the model is designed to be extracted from the mould during production.

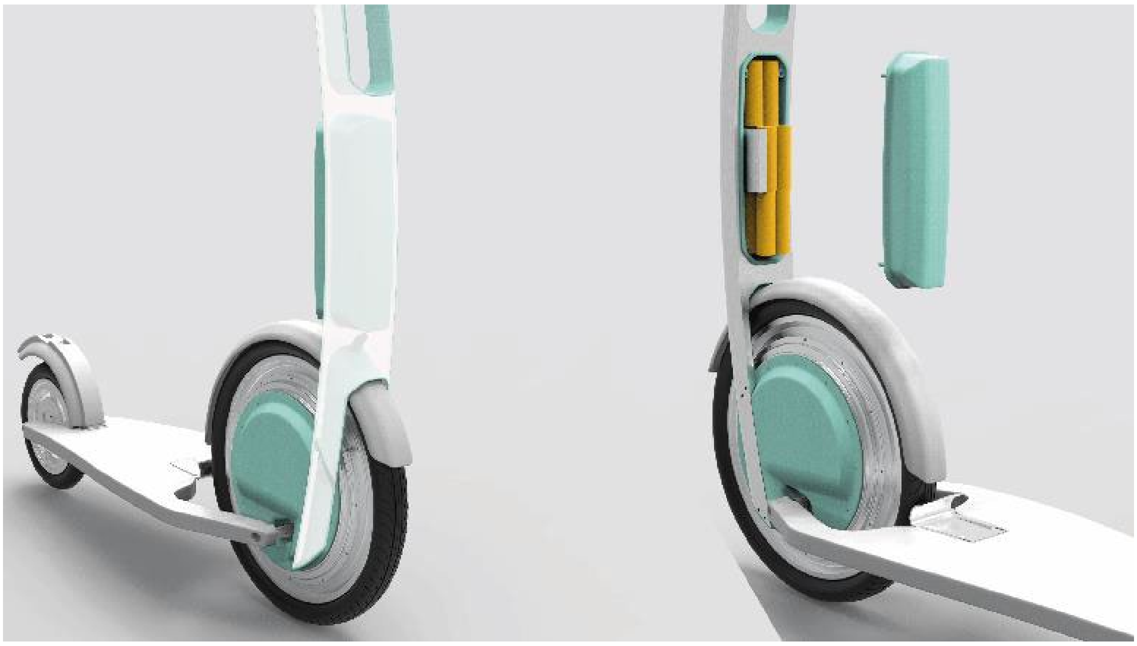

Figure 10. Overview of the auxiliary and fixed battery case configuration.

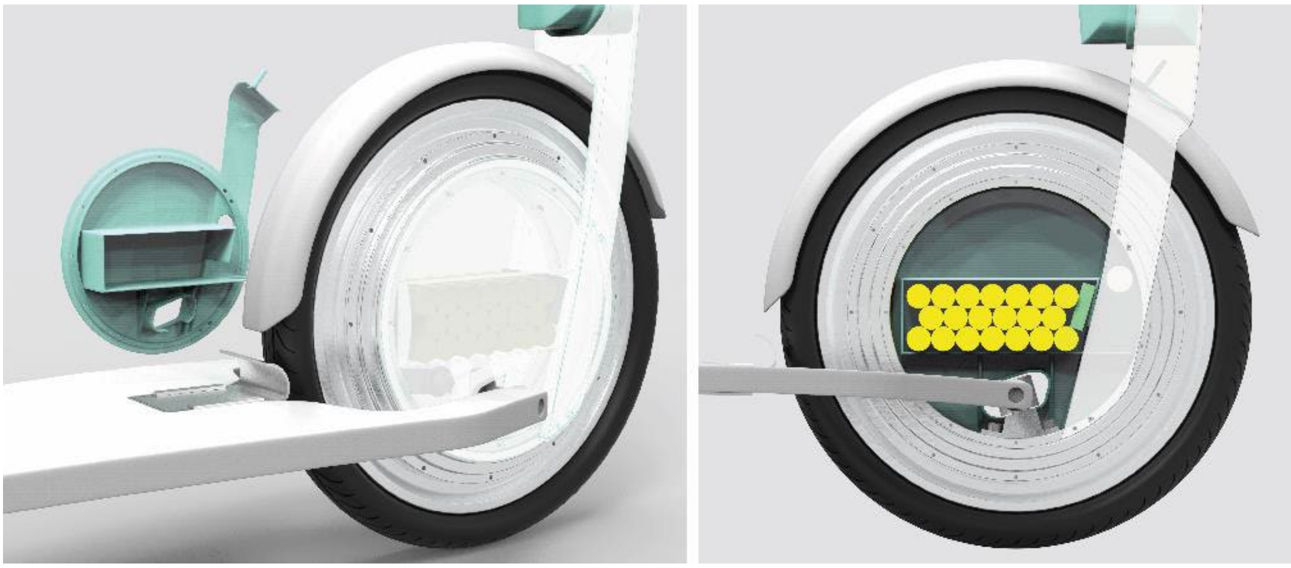

Figure 11. Overview of the fixed battery case configuration.

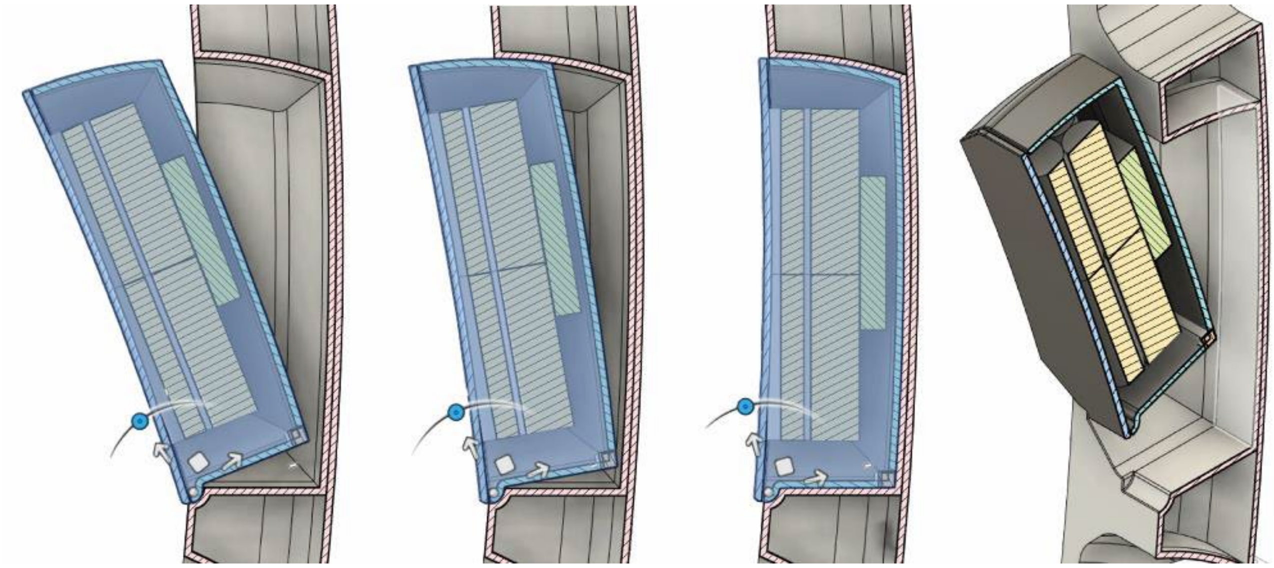

Figure 12. View of the case battery model profile and two/three-dimensional representation of how the user should fit it in the steering column.

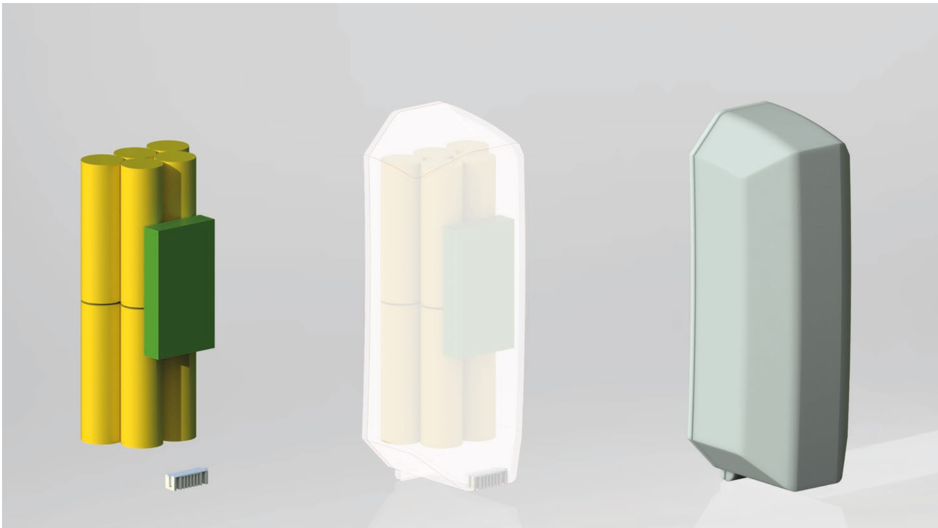

Figure 13. Overview of the 3 categories of components' configuration.

4.5. Research Direction #4: Assembly Designing

"Deliver Phase" Results: Assembly Prototyping and Testing

The closing of the research process, in correspondence to the end of the second diamond, combines the research directions findings in a single product assembly: the newly silent, clean, energy-efficient, and safe microvehicle. This blended version of the existing personal light electric vehicle employs a control mechanism, where, similar to the monowheel mechanisms, the users push the steering column to accelerate and pull it for decelerating.

This highly improves the perceived user experience. Indeed, the remote quantitative usability testing highlights a positive response to the question "Perspicuity. Is it easy to get familiar with the product and to learn how to use it?", with the following results: 14.8% voted 4/7; 33.3% voted 5/7; 37% voted 6/7; and 14.8% voted 7/7.

Following the manufacturing process conducted by the partner companies, the research team develops the first generation of the scooter physical prototype (presented in Figure 14), which consists of (i) the location of the main axle at the lower part of the front wheel; (ii) the steering column; (iii) the presence of the fixed battery compartment and the corresponding 3D printed case; and (iv) the platform, which is made of a sandwich structure.

As shown in Figure 14, some components are rapidly prototyped through additive manufacturing, e.g., the fixed battery storage; others are only prototyped in the virtual environment through Solidworks and visual renderings, e.g., the auxiliary battery; and others are purchased to enable the assembly prototyping, e.g., the headlight, handlebar and rear wheel.

Figure 14. First generation of the kick scooter prototype.

5. Discussion

This paper's introduction highlights how interdisciplinary collaboration in the design of urban mobility products could be a source of value creation. The researchers, therefore, structured a critical literature review on design thinking and highlighted the coherent Design Framework for Innovation and the Double-Diamond design thinking model as important methods to overcome research challenges and define disruptive and novel outputs in a transdisciplinary way. Hence, the cross-disciplinary research team evaluated the findings in the context of the H2020 LEONARDO project, which addresses the limitations of current micromobility solutions.

As discussed in the last two sections, the results of the present research context confirmed the assumption and set the basis for re-elaborating the design model, as presented in Figure 1. Notably, the application of the methods and tools relating to the first diamond widened the opportunities to conceptualize the overall model. The analysis and synthesis of the data gathered in the research phase indeed provided the researchers with different inquiry directions to be addressed, supporting the development of the electric microvehicle. These findings set the basis for splitting the current strategic design brief into four research directions, relating four different product components and the corresponding assembly prototyping, which fall under the mutual objective of designing an innovative micromobility vehicle based on the smart fusion of the monowheel and kick scooter concepts. Moreover, regarding how many inquiry directions were identified by the research team, the research tasks of the second diamond were addressed four times; they were addressed one additional time to merge the final results in the product assembly. These results were fundamental in clarifying the design research process for the innovative development of urban transport products.

Figure 15 presents a graphical summary of the discussions. In other words, the research team framed "an interdisciplinary Double-Diamond design thinking model for urban transport product innovation" characterized by (i) guidelines for organizing and structuring the research process, as shown in Figure 16; (ii) macro- and micro-design research tasks to be addressed, as shown in Figure 16; (iii) interdisciplinary methods and tools to be undertaken, as shown in Figure 16; and (iv) a novel interpretation of the second diamond, as shown in Figure 15. Notably, the macrotasks and microtasks related to the following steps: (i) identifying the macrotrends through in-depth analysis of the topic; (ii) understanding the context of the problem through in-depth analysis of the brief, in-depth analysis of the project partners, in-depth analysis of the product, mapping of the research areas, and framing of the research methods; (iii) empathizing through in-depth analysis of the stakeholders and in-depth analysis of the user interactions; (iv) technological advancements through secondary research; (v) analyzing through in-depth analysis of the data collected; (vi) synthesizing through mapping of the knowledge resources and framing "product assembly components"; (vii) co-designing insights through co-designing insights; (viii) designing the strategic brief through mapping of the research opportunities areas and defining research questions; (ix) developing the strategic brief through the framing of the research methods; (x) co-designing disruptive ideas through formal exploration; (xi) iterating through iteration tasks; (xii) exploring the idea selected through the framing of the research methods; (xiii) prototyping through prototyping in a virtual environment, rapid prototyping, and physical prototyping; and (xiv) testing through remote quantitative usability testing and testing in accordance with regulations.

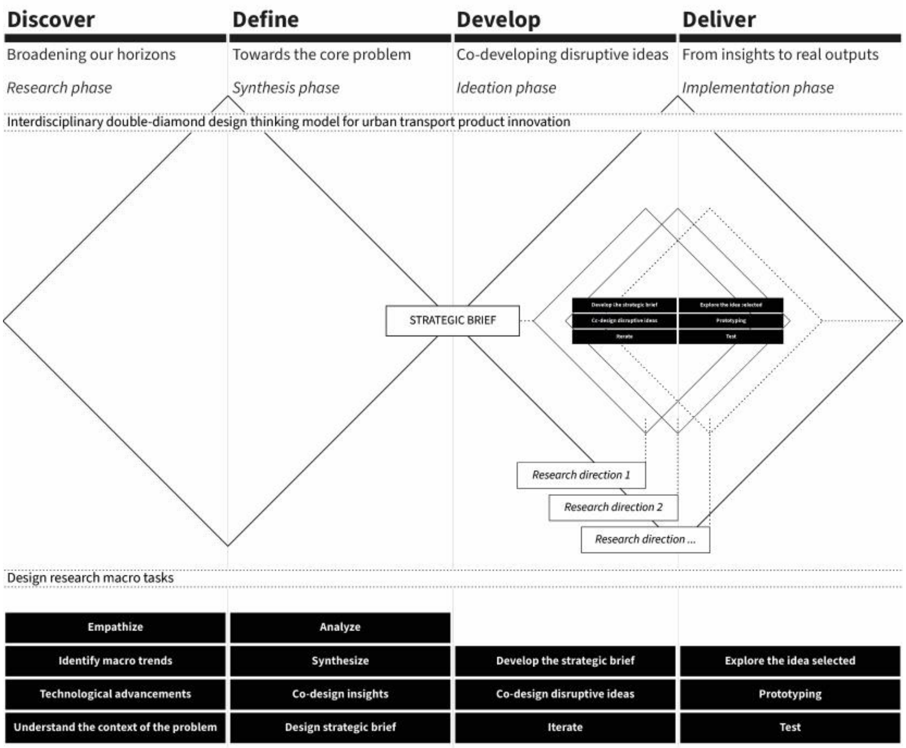

Figure 15. Interdisciplinary Double-Diamond Design Thinking model for urban transport product innovation. The figure presents the novelty of the design model and the corresponding research macro-tasks. Re-elaboration of the "Double-diamond design thinking model" [29].

Figure 16. Interdisciplinary Double-Diamond Design Thinking model for urban transport product innovation. The figure presents the design research macro- and micro-tasks and tools and methods to employ for mobility product innovation. Re-elaboration of the "Double-diamond design thinking model" [29].

The fourth feature of the design model highlights the actual diversification compared to the Double-Diamond presented in Figure 1. Notably, it emphasizes the parallel development process of the product components, the recurring adoption of the research activities for each research direction, and how these research directions are inscribed in the second diamond, between the "Develop" and "Deliver" phase, or rather in the stages where the research team should develop and implement the product assembly.

Therefore, the research team widens the vision of the second diamond, showing it foresees a constant and repetitive adoption of the research tasks for every research direction, identified by the design practitioners at the end of the initial phase of the process. The researchers highlight and support the need to identify and map the components of the mobility product assembly to delineate a wider variety of design potentials and give design experts more opportunities to visualize insights for interventions.

6. Conclusions

In conclusion, the research team adopted the Double-Diamond Design Thinking model in a transdisciplinary context to develop an innovative micromobility vehicle. Notably, they designed the hierarchical research process, the four stages of development, and the macro- and micro-tasks to undertake an innovative micromobility solution, involving tools and methods that are employed in the four stages of development. The project research context of "Leonardo" is an exploratory case study in which the team sought to answer the research questions through the application of the Double-Diamond model. During the process, the team correlated and employed mixed methods in both the design and engineering disciplinary sectors, involving stakeholders, project experts, design and engineering researchers, and practitioners through the design of participative research activities. The researchers obtained both qualitative and quantitative data. Consequently, the emerging findings set the basis for the iteration of the graphic representation of the design model and led to the framing of the "Interdisciplinary Double-Diamond Design Thinking model for urban transport product innovation". This design model aims to let design and engineering researchers and practitioners adopt, replicate, and scale the process the team developed. Finally, the research team argues this novel design model has the potential, as a design research instrument, to be capable of addressing sustainable mobility and guiding interdisciplinary design research, design practice, and education in the industrial engineering and design disciplinary sectors.

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