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Modular and Adaptive Approach for Advancing Innovation and Sustainability in Light Vehicles Design

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Featured Application

This study offers a design-driven framework for designing modular bicycles and cargo bikes capable of adapting to diverse users, contexts, and production requirements. By illustrating how frame-level modularity enables configurable, upgradable, and user-centered vehicle architectures, the work provides actionable guidance for manufacturers, mobility planners, and design teams. Potential applications include modular bikes and cargo bikes for urban logistics, shared mobility fleets, and personalized commuting, where enhanced versatility, simplified maintenance, and scalable adaptation support evolving operational needs.

Abstract

This paper reports part of the research results carried out within the National Centre for Sustainable Mobility (MOST—CN4)—Spoke 5 "Light Vehicle and Active Mobility"—funded by the Italian National Recovery and Resilience Plan (PNRR). Specifically, it presents the design of a bicycle frame based on the pursuit of maximum modularity and adaptability. The research investigates multi-level modularity as a strategic design lever to improve flexibility, usability, and production efficiency in light vehicles. A design-driven and interdisciplinary methodology combined a systematic analysis of 76 patents with a qualitative cross-comparison of 15 case-study products and collaborative co-design activities involving domain experts. The resulting insights informed the development of a modular bike frame prototype, enabling evaluation of user-centered adaptability, production-oriented modularity, and functional transformations such as e-bike integration and cargo configurations. Findings provide evidence-based, qualitative insights and practical design exploration for modular light vehicle development, offering an operational framework and laying the groundwork for a structured, generalized framework to guide future research and industrial applications.

Keywords: urban mobility; sustainable mobility; micromobility; modeling of urban mobility; modularity; bike; cargo bike; light vehicle design

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1. Introduction

Urban mobility is increasingly recognized as a major challenge for achieving environmental and social sustainability in contemporary cities [1–4]. Rising traffic congestion, deteriorating air and noise quality, and persistent inequalities in access to transport services negatively affect citizens' well-being and pose substantial risks to public health. These conditions limit urban areas' capacity to pursue sustainable social and economic development and highlight the need to rethink traditional mobility paradigms [1–4].

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In response, urban mobility systems are therefore undergoing a significant transformation. This shift aims to reduce private car dependency, improve environmental quality, and enhance accessibility in densely populated urban and peri-urban areas [5–7]. This transition is supported by evidence in multiple disciplines, including urban planning, economics, engineering, and mobility design, which converge in identifying new business models, reconfigured infrastructures, and innovative sustainable technologies as central levers of change [5,6]. On this view, contemporary urban mobility models increasingly rely on the convergence of technological innovation and novel service logics [8], grounded in principles of flexibility and decisional autonomy for individual travelers [9].

Within this evolving mobility landscape, micromobility solutions, including bicycles, e-bikes, and cargo bikes, are recognized as strategic key models to define new sustainable urban transport systems [10]. These lightweight, energy-efficient and low-impact vehicles particularly support first and last-mile travel and flexible intermodal movement for both logistic and private use [11–15], providing multiple environmental and operational benefits that reinforce their role in sustainable urban mobility.

Environmentally, micromobility vehicles reduce greenhouse gas emissions, air pollutants, urban congestion, and energy consumption [10,16–18] while generating substantially lower noise [19] compared to motorized vehicles [20].

Operationally, micromobility solutions enable flexible travel behaviors, allowing route choice and parking adaptability, reducing dependence on large vehicle infrastructure, and improving access to constrained or pedestrianized areas [10,16,18].

In urban logistics, bicycles and cargo bikes have been shown to improve delivery efficiency for short-range trips by reducing travel times in congested areas and supporting more distributed, neighborhood-level distribution strategies, complementing or even replacing conventional centralized hub models [14,15,21,22]. Similarly, micromobility private and shared urban transport provide scalable solutions for first and last mile connections, enabling users to navigate dense urban environments efficiently, and integrating with public transport networks [10,23].

Overall, micromobility's environmental, acoustic, operational, and societal benefits underscore its strategic role in fostering flexible, resilient, and user-centered urban mobility systems [10,16,18].

Despite their potential, current micromobility solutions often lack adaptability to diverse users and contexts, exhibit limited performance, and remain constrained by infrastructure gaps present in many urban areas [24–28]. Such limitations can significantly reduce the attractiveness and long-term adoption of light vehicles, particularly among user groups not yet fully engaged with these modes, who continue to perceive them as inflexible and difficult to integrate into daily mobility practices [24–28]. These challenges are relevant for bicycles and cargo bikes; although technologically mature and standardized, they retain substantial potential for innovation where restricted versatility, insufficient cargo capacity, storage constraints, and fragmented product families limit operational and user flexibility.

Addressing these issues requires a dual approach, integrating top-down strategies aimed at improving mobility models, urban infrastructure, and regulatory frameworks [29–31], with bottom-up, vehicle-level innovation focused on design, performance, and adaptability [32–34]. While top-down measures create safe and accessible environments, bottom-up approaches ensure that micromobility solutions meet diverse operational and user needs, enhancing both usability and inclusivity.

Bottom-up research in micromobility increasingly emphasizes ergonomics, ride comfort, and user-vehicle interaction, recognizing that interventions at the vehicle level can directly influence perceived usability, safety, and adoption [35–37].

Technical studies of vehicle dynamics, such as vibration exposure, ride smoothness, and shock transmission [38,39], provide quantitative and qualitative insights that can inform design-driven strategies for handlebar configuration, seating ergonomics, suspension systems, and overall frame architecture [35,37]. These interventions, although focused on individual vehicle performance, have broader implications by mitigating behavioral barriers and promoting sustained use of light vehicles.

From a complementary perspective, seemingly simple technical innovations can enable systemic changes in mobility patterns. A well-established example is the folding bicycle [32], whose reconfigurable structure facilitates seamless intermodality, demonstrating how targeted design interventions can reinterpret traditional vehicle typologies to meet evolving operational and urban mobility needs. Such vehicle-level adaptability can expand the functional use of micromobility, supporting first and last mile travel, shared mobility, and neighborhood-level logistics, and in turn reinforcing integrated and flexible urban mobility systems.

Taken together, these examples illustrate the strategic role of bottom-up, design-driven innovation: at the micro level, it enhances comfort, safety, and performance; at the macro level, it shapes mobility behaviors, opening new usage scenarios and complementing top-down infrastructural and regulatory measures. This highlights the importance of research that leverages product-level design to strengthen broader urban mobility strategies, fostering flexible, resilient, and user-centered micromobility systems.

On these premises, the paper reports research and design activities conducted within the National Centre for Sustainable Mobility (MOST—CN4)—Spoke 5 "Light Vehicle and Active Mobility", funded by the Italian National Recovery and Resilience Plan (PNRR) [40]. The results described concern the Work Package (WP) 2.1—Vehicle Design, Materials and LCA—activities, which addressed the design and development of light pedal-assisted vehicles, including an e-bike and an e-cargo bike. These vehicles were intended to achieve a short-term technological readiness level (TRL 6) and to be deployed across heterogeneous urban and social contexts, integrating both individual and shared mobility needs [40].

One of the specific objectives of Work Package (WP) 2.1 was to investigate modularity as a strategic design principle, exploring how it can enhance the adaptability, versatility, and sustainability of light vehicles. To this end, modularity was examined at multiple levels: (i) enabling configurable and upgradable vehicle architecture, (ii) supporting personalized and inclusive user experiences, (iii) expanding operational scenarios, and (iv) improving scalability, production efficiency, and cost-effectiveness, across both individual and logistics applications [40].

Starting from this multi-level perspective, the paper presents the results of research activities investigating the design and development of a modular bicycle frame. The contribution of the paper lies in demonstrating how insights from modularity research can guide the design of light vehicles capable of responding to diverse operational and user requirements. By combining analytical investigation with applied concept development, modularity is framed not merely as a technical attribute, but as a strategic principle to promote inclusive, flexible, customizable, and sustainable urban mobility solutions.

On this level, the study presents a practical, project-based framework, in which the description of the research and design workflow itself serves as a structured and replicable approach for the development of modular bicycle frames. This design-driven framework integrates engineering and industrial design insights, detailing the systematic application of modular strategies and disassembly methods throughout the project.

Building on this practical experience, the findings also lay the groundwork for a structured, generalized framework, which transcends the specific strategies investigated on the current project. This framework aims to inform future modular light vehicle initiatives, providing a conceptual and methodological reference for research and industrial applications beyond the present case study.

2. Modularity Background

2.1. Overview

Modularity is an approach for organizing complex products and processes efficiently [41]. It consists of a set of design and organizational strategies that enable the management of complex systems by decomposing them into independent and interoperable components within a coherent whole [42]. This decomposition is grounded in the principle of loose coupling [43,44], whereby elements developed and manufactured separately can be combined in multiple configurations without compromising the overall integrity of the system [45,46]. Complementing this logic are the standardization of specifications and the explicit definition of interfaces, which establish the architectural "rules" of the system and determine both the compatibility between modules and the degree of freedom in mixing and matching parts [47].

While this technical definition clarifies how modularity functions, the framework proposed by Baldwin e Clark [48], which represents a model subsequently taken up by other authors, explains its impact by identifying where and why modularity creates value. Their model articulates an evolutionary interpretation of modularity across three distinct yet interconnected levels: (i) Modularity in Production (MiP), concerning the organization of manufacturing processes and the possibility of assembling and replacing components efficiently, thereby supporting standardization and supply chain management; (ii) Modularity in Design (MiD), which refers to the intentional decomposition of the product architecture into independent units linked by standardized interfaces, enhancing design flexibility and innovation potential; (iii) Modularity in Use (MiU), defined as the extent to which end users can reconfigure, personalize, or upgrade the product according to their needs, generating value through versatility, simplified maintenance, and extended product lifecycles.

MiD, MiP, and MiU each retain their own logic and specific benefits, but importantly, they can also operate in continuity along the product lifecycle, emphasizing modularity not merely as a physical property of components but as a strategic multi-level principle that connects product architecture, operational processes, and potential user interactions. Modularity in Design (MiD) establishes the architectural decomposition and interface structure that mediates both industrial and user-facing forms of value. As argued by Fixson [49], product architecture determines how design decisions propagate into manufacturing, supply chain, and maintenance processes, thereby linking MiD and MiP through a shared logic of standardization, interface management, and process alignment. At the same time, MiD provides the structural conditions that may enable MiU: the definition of independent modules and standardized interfaces not only facilitates production but also establishes the technical foundation for user-driven adaptation, personalization, and functional reconfiguration.

Building on the interdependent roles of MiD, MiP and MiU, bicycles (and cargo bikes) provide an emblematic example of how modularity materializes at the product level, exemplifying a multi-level interplay of design, production and user adaptation.

As noted by Galvin and Morkel [50], most of bicycle's components are governed by international standards consolidated over more than fifty years, positioning the bicycle industry among the sectors with the longest-standing tradition of component interoperability (MiD). This mature modular architecture, supported by established standards and norms, not only enables streamlined manufacturing, assembly, and maintenance processes (MiP) but also provides a structural foundation for user-driven adaptation and customization

(MiU). In particular, the modular logic of bicycles and cargo bikes centers on the frame as the structural core and primary connector (MiD), to which replaceable components (wheels, saddles, handlebars, transmissions, braking systems, luggage racks, cargo boxes, accessories) can be connected, combined, updated or modified without compromising the functional integrity of the vehicle.

From a production perspective (MiP), this approach supports efficient assembly, standardization, and component interchangeability across different models, while also facilitating maintenance and lifecycle management by allowing individual parts to be replaced or upgraded independently. From a user perspective (MiU), the same modular configuration provides flexibility for personalization, ergonomic adjustments, and functional adaptation, such as adding cargo modules or child seats.

Overall, studies highlight two complementary levels of modularity investigation in cycling. The first focuses on the supply chain, addressing standardization, assembly, component management, manufacturing logic [42,50], as well as logistics and economic strategies. The second examines individual "modular elements," analyzing their potential for inclusion in existing systems and the implementation of specific functionalities [14,33,51–54]. These perspectives reinforce the dual role of modularity in supporting both production efficiency and user-oriented flexibility, as introduced in the previous discussion.

While most studies concentrate on predefined modules or isolated production processes, fewer contributions specifically address modularity at the structural frame level. Notably, Shoval et al. [55] explores the frame as a dynamic modular architecture, showing how its configuration can evolve over the product lifecycle to support maintenance, upgrades, and adaptation to changing operational needs.

This orientation informs the present study's focus on the bicycle frame as the primary structural architecture, where modular design choices can support production efficiency and enable user-driven adaptation. By analytical and practical exploration of Modularity in Design (MiD), the study assesses how the frame, as a set of independent modules, can generate value across dimensions of Modularity in Production (MiP), facilitating assembly, standardization, and maintenance, and Modularity in Use (MiU), enabling user adaptation to different urban scenarios, transport needs, and functional configurations.

In this way, the study moves the understanding of modularity from individual components or systemic manufacturing logics to overarching product architecture, exploring how architectural modular frame solutions (MiD) may expand the interplay between production-oriented efficiency (MiP) and user-centered adaptability (MiU).

2.2. Formulation of the Research Questions (RQ)

Building on the conceptual categorization of modularity at its three levels, Modularity in Design (MiD), Modularity in Use (MiU), and Modularity in Production (MiP) [48], the study formulated a set of research questions to guide the starting analytical project investigation. These questions were intended to focus the desk research, on understanding how design-level modularity (MiD) can inform potential implications for both user-centered adaptability (MiU) and production efficiency (MiP).

The first step defined a broad Research Question (RQ) to guide the investigation and establish the design space for modular bicycles and cargo bikes. Modularity was interpreted as the ability to disassemble, reconfigure, and recombine elements of a light vehicle frame, considering both technical feasibility and user experience implications.

Based on these premises the following main RQ was formulated: How can modularity, as a design lever of innovation, inform strategies that enhance adaptability and usability to improve user experience, or support structurally coherent, efficient, and sustainable production architectures?

To operationalize this investigation, the following specific questions were defined:

- RQ-1a (MiD Exploration): Which configurations and assembly strategies are most recurrent, and how might they guide the identification of innovative modular solutions?
- RQ-2a (MiD Exploration): What gaps or limitations exist in current modular approaches that warrant further exploration in design development?
- RQ-3a (From MiD to MiU): How is MiD currently realized in existing bicycles and cargo bikes, and what opportunities might it present for user adaptability?
- RQ-4a (From MiD to MiP): How is MiD currently realized in existing bicycles and cargo bikes in ways that could inform production efficiency and standardization?

3. Materials and Methods

3.1. Overall Methodological Approach

The theoretical background on modularity provided the foundation for identifying potential design opportunities related to bicycle and cargo bike frames, highlighting how concepts such as personalization, operational flexibility, and production efficiency (MiU, MiP) can be translated into actionable design levers [48].

Building on these premises, the research adopted the Double Diamond Design Thinking model, which structured the design workflow into two iterative phases of divergence and convergence exploration. The first diamond (Inspiration phase—Discover step followed by Define step) supported the analysis and clarification of the problem space, while the second (Ideation phase followed by Implementation phase) guided the generation, refinement, and implementation of design solutions [56,57].

To articulate the relationship between analytical and design activities, the methodology integrated Research for Design (RfD) and Research through Design (RtD) approaches [58–60]. RfD informed the structuring of the analytical investigation, while RtD provided the basis for generating knowledge through design experimentation. Within this methodological configuration, the two diamonds served complementary roles.

The first diamond was employed to map how modularity is currently addressed in bicycle and cargo bike frames through patent and case studies analysis, aiming to identify opportunities, recurrent patterns, and structural principles emerging from existing solutions. These activities were guided by the research questions presented in Section 2.2.

The second diamond guided the exploratory design activities. During the Ideation phase, collaborative design sprint sessions were conducted to generate modular configurations oriented toward modularity in use (MiU) and modularity in production (MiP). The subsequent Implementation phase focused on selecting the most promising strategy and advancing its development.

To maintain clarity and traceability between analytical evidence and design output, the overall methodology was operationalized through a sequence of interconnected activities: (i) patent prior art analysis and clustering, (ii) case study research and cross-comparison, (iii) synthesis of emerging insights and reformulation of design-oriented research questions to support ideation phase, (iv) co-design activities through design sprint sessions, (v) iterative refinement and focus group for evaluating and selecting the most promising strategies of modularity, (vi) development and prototyping of definitive solution and concept exploration of implications for MiU and MiP.

Within this structure, points (i) and (ii) correspond to the Inspiration phase (Section 3.2), (iii) functions as a strategic transition enabling the shift toward design exploration (Section 3.3), (iv) and (v) constitutes the Ideation phase (Section 3.4), and (vi) correspond to the Implementation phase (Section 3.5).

Below, Figure 1 illustrates the overall workflow based on Double Diamond model.

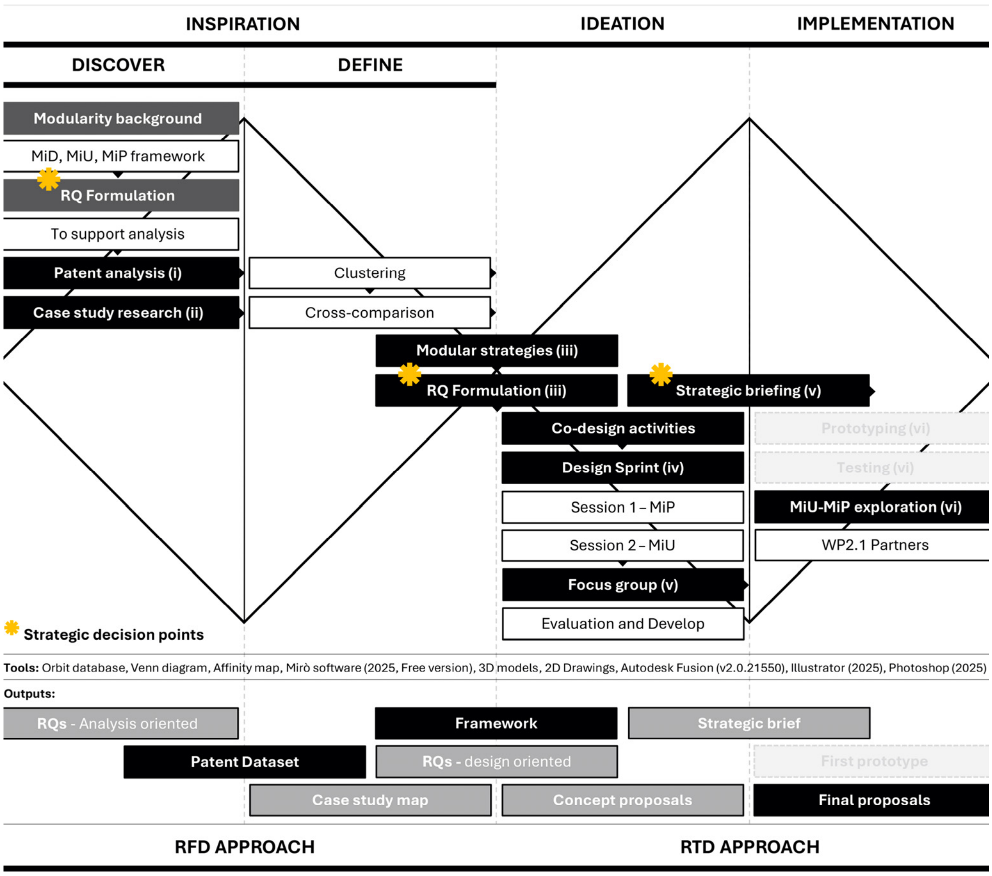


Figure 1. Overall workflow diagram based on the Double Diamond Design Thinking model. The main steps of the workflow (i–vi) are highlighted in black, with methodological and activity insights in white. Beneath each phase, key outputs are shown. This representation illustrates how analytical and design activities progressively inform the development of user and production oriented modular bicycle frames.

Each activities step generated specific outputs that informed the transition to the next phase and progressively narrowed the design spaces toward feasible strategies. Prior to step (i), the theoretical framing of modularity [48] and the formulation of the research questions constituted an initial strategic decision point that defined the problem space and guided the analytical phase. In step (i), the patent prior art analysis and clustering produced a structured dataset of existing modular light vehicles and a preliminary clustering of MiU and MiP strategies, providing an overview of how modularity has been technically implemented in bicycle and cargo bike frames. The output of (i) supported step (ii), where a case study research and cross comparison led to the identification of recurring patterns between technical possibilities and product offerings.

The synthesis of insights from step (i) and (ii) in step (iii) led to a reformulation of the RQs into design-oriented terms, establishing a key decision point that enabled the transition from analytical investigation to design exploration. Step (iv), introducing collaborative design activities, generated multiple modular configuration concepts oriented toward MiU and MiP. The subsequent iterative refinement in step (v) resulted in the elaboration of a strategic brief outlining the most promising modular criteria and establishing a second key decision point that guided the planning and coordination of the research team's subsequent activities.

Finally, step (vi) involved the development and prototyping of a preliminary modular frame solution and conceptual outputs for assessing the interplay between design decisions (MiD), production processes (MiP), and user adaptation (MiU).

3.2. Inspiration Phase

3.2.1. Patent Prior Art Analysis and Clustering

Patent documents represent a rich source of technical knowledge [61]. This makes them particularly valuable for understanding how modularity and dismountability are interpreted in mechanical solutions, and for identifying recurring principles in light-vehicle design from a MiD perspective [48].

For this reason, building on the research questions described in Section 2.2, a systematic patent prior art analysis was conducted, using the international patent database "Orbit" [62], with two complementary objectives: (i) to understand how the concepts of "modularity" and "dismountability" are addressed in existing technical solutions, and (ii) to identify recurring themes, terminologies, and design approaches that could inform subsequent ideation and design development phases.

The methodology followed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines [63]. The workflow included the following steps: (i) development search strings; (ii) screening of sources and exclusion of irrelevant entries; (iii) identification of peer-reviewed patents and removal of duplicates; (iv) eligibility assessment of full-text patents; and (v) thematic analysis and clustering of the selected patents. To refine the search and capture the breadth of modularity concepts, the investigation point (i) and (ii) were organized into three exploratory, subsequential steps, each building upon the insight of the previous one.

Step 1 used the keyword "modular" combined with variations of the term "bike" to identify a preliminary core set of patents and to analyze how the concept of modularity is described in patent texts (for the complete search string see Table A1, Appendix A).

Insights from Step 1 allowed the identification of synonyms, lexical variations, and related terminology for expressing the ability to "separate", "modify", "reassemble", or "transform" the frame vehicle. This led to the definition of a second set of more specific adjectives describing modular features: "detachable", "demountable", "dismountable", "removable", "divisible", "dividable", "splittable", "disassemblable".

In Step 2 these keywords were combined with the same vehicle-related terms used in Step 1 by treating them as two separate clusters: "adjective" and "vehicle (see Table A2, Appendix A). However, this cluster-based strategy produced a large number of partially relevant results. For instance, general prefixes such as "remov*," "divid*," or "divis*" retrieved patents focusing on minor components (e.g., lights, wheels, cranks) or on folding mechanisms, which were excluded from the analysis as the study focused on structurally disassemblable frames. Likewise, generic vehicle terms such as "cycle" returned results outside the cycling domain, including applications from chemistry, physics, or biology.

For these reasons, Step 3 tested each adjective individually in combination with each vehicle variant within a single search string (see Table A3, Appendix A). This allowed the identification of those adjectives most effective in capturing relevant inventions for frame disassembly and modular configuration while reducing off-topic patents.

The patents retrieved through Steps 1–3 were optimized for thematic consistency and duplicates were removed. Patent status (e.g., active, expired, pending, regional application) was not used as an exclusion criterion; instead, selection focused on content relevance, specifically the identification of structural solutions, disassembly methods, and design strategies (MiD) with potential implications for MiU and MiP.

The retained patents were then examined individually and classified through qualitative thematic analysis to identify recurring design principles and mechanisms associated with frame-level modularity in bicycles and cargo bikes.

This classification served as an intermediate analytical output and produced a preliminary framework of modularity strategies, structuring the solution space into comparable clusters. This framework provided the basis for the subsequent methodological step, in which case studies were cross compared to examine how such strategies are operationalized in practice.

Below, Table 1 summarizes the systematic process of patent analysis and screening.

Table 1. Workflow of patent identification, screening, and thematic clustering for modular and detachable bicycle and cargo bike frames.

Preparation [1]					
Development of keywords and related search strings on three progressive phases					
Step 1		Step 2		Step 3	
Search string 1		Search string 2		Search string 3	
Identification					
No. of record identified through database searching					
Identified		Identified		Identified	
174		1420		1436	
Screening 1					
Identification of peer-reviewed sources					
Patent	Excluded	Patent	Excluded	Patent	Excluded
14	160	17	1403	61	1375
Screening 2					
Grouping of obtained results and elimination of duplicates					
		Patent	Duplicates		
		92	16		
Eligibility					
No. of full-text articles assessed for eligibility					
76					
Analysis					
Thematic analysis of the content, extrapolation and clustering					

[1] Search conducted on patents documents published between January 1990 and June 2024, applying filters to keywords appearing in the title and abstract only.

3.2.2. Case Studies Cross-Comparison

To contextualize the modularity strategies applied to vehicle frames identified in the patent analysis, a complementary qualitative case studies approach was adopted [64,65]. This aligns with Gerring's conceptualization of purposive cases selection, where cases are retained for their ability to elucidate theoretical constructs rather than for statistical representativeness [65].

The objective of this phase was to examine how the modular principles emerging from the patent classification are implemented in existing vehicle's configuration. Whereas patents describe structural intentions, technical mechanisms, and functional rationales (MiD), allowing the extraction of modularity principles from a design-oriented perspective with implications for production (MiP) and use (MiU), the case studies made possible to observe how these principles are operationalized in practice. This included the collection of insights on manufacturing processes, material adoption, reconfiguration pathways and use contexts that cannot be fully inferred from patent documentation alone.

Case selection followed three qualitative criteria: (i) presence of structural modularity (full or partial), (ii) availability of technical information, and (iii) coverage of the modularity clusters resulting from the patent analysis. In line with Gerring [65], cases were retained for their capacity to maximize conceptual insights, that is, to reveal variations across the phenomenon rather than to achieve statistical coverage.

The selected cases include both commercially available vehicles as well as research-driven or conceptual prototypes. Including these latter categories expands the considered design space beyond currently industrialized products, exposing emergent solutions that indicate potential future trajectories.

As discussed in Section 2.1, literature provided limited coverage of frame-level modularity in bicycles and cargo bikes. While modularity is discussed in adjacent domains (e.g., component design, shared mobility systems, supply chains), detailed accounts of modular frame architectures are less discussed. To assemble relevant case studies, the analysis therefore drew on both academic and grey literature offering technical and design-oriented information on emerging mobility products. Source included: (i) market listings from commercial retailers and manufacturers, (ii) awarded design products from major international competitions (e.g., Red Dot [66], IF Design Award [67]), (iii) research driven prototypes from EU-funded mobility projects, and (iv) conceptual proposal documented through sector-specific media.

These sources collectively enabled access to solutions ranging from industrialized configurations to speculative prototypes, thereby covering distinct stages of technological maturity. The inclusion of commercial listings enabled the identification of solutions that have reached market maturity and industrial feasibility. Design award archives provided curated access to emerging innovation pathways filtered through expert juries. EU-funded prototypes offered insights into research-oriented proofs of concept and technological experimentation, while sector-specific media captured conceptual and speculative directions not traceable through market or research outputs.

The investigation served an illustrative purpose: to qualitatively visualize modular trajectories across real and prototypical vehicles and extract operational insights that complement the patent-derived clustering.

3.3. Transition from Analytical Phase to Concept Ideation

The Inspiration Phase provided the analytical foundation necessary to support the subsequent Ideation and Implementation activities. Insights from the patent and case studies analysis were essential to frame the problem space, clarify the dimensions of modularity to be investigated, and prepare the ground for co-design work.

Building on these foundations, design-oriented research questions (RQs) were formulated to guide early-stage co-design activities through Design sprint sessions aiming to investigate how MiD could inform MiU and modularity in production MiP.

These RQs served to mediate between the constraints and opportunities emerging from the analysis and the open-ended nature of design sprint activity, ensuring that ideation remained evidence-informed yet flexible. By framing the design exploration without imposing a rigid brief, the methodology enabled flexible development, rapid experimentation, and the emergence of novel solutions.

Beyond supporting the formulation of targeted RQs, the analytical phase generated operational knowledge and insights that guided the subsequent design process.

3.4. Ideation Phase

The ideation phase was organized as a structured sequence of co-design activities aimed at generating, refining, and evaluating preliminary modular solutions for bicycle and cargo bike frames.

The process began with early-stage Design Sprint sessions [68,69] coordinated by researchers at the IDEE Lab, University of Florence involving professional designers and other domain experts (No. 8 of partecipants).

These sessions followed a condensed one-day format process [70] divided as follow: (i) idea generation using the How Might We (HMW) technique (10 min); (ii) creation of an affinity diagram by grouping and sharing HMW statements (20 min); (iii) voting process to select the preferred HMW questions (5 min); (iv) Sketching via Crazy 8s to rapidly explore multiple solutions (20 min); (v) Re-elaboration of sketches for refinement (20 min); (vi) Storyboard creation of selected concepts (40 min); (vii) Presentation and sharing of group outcomes (20 min); (viii) Rapid prototyping of selected solutions (60 min); (ix) Pitch presentation of final elaborations (40 min).

The outputs of these sessions produced a set of initial modular concepts and insights that captured diverse approaches to modularity in design (MiD) refined and developed through a structured iterative phase of evaluation and exploration.

This phase involved the team of product designers and researchers at the University of Florence and the WP2.1 partners of Dept. of Engineering and Applied Sciences (DISA) and Dept. of Management, Information and Production Engineering (DIGIP) at the University of Bergamo, with the cooperation of the company Dedacciai Strada—Dedaindustrie S.r.l.

Through structured focus groups, participants collaboratively examined the technical feasibility, functional adaptability, and production implications of the refined modular solutions proposed. Feedback and observations collected during this stage informed the prioritization of promising concepts and operative strategies directions.

By integrating exploration design sprints suggestion with iterative multi-domain expert evaluation, the methodology ensured that the ideation process was evidence-informed, participatory, and capable of producing a strategic brief, technically grounded, and user-centered.

3.5. Implementation Phase

Building on the strategic brief, the Implementation Phase aimed to operationalize the most promising modular strategies and concept solutions.

A reference gravel bike frame (Polvere Titanio model) was provided by the industrial partner Dedacciai Strada—Dedaindustrie S.r.l., to serve as a technical platform for development activities while maintaining compatibility with dimensional and production constraints. The supporting documentation included the 3D CAD model and technical executive drawings for all available sizes (S, M, L, XL).

Development tasks were distributed according to WP2.1 partner expertise. The University of Bergamo in collaboration with Dedacciai Strada—Dedaindustrie S.r.l. focused on the engineering, prototyping, and testing of the enabling modular component (a structural joint) allowing frame disassembly and reconfiguration. This activity primarily addressed Modularity in Design (MiD) through the definition of technical interfaces, material selection, and prototype validation on the reference gravel frame.

The University of Florence was responsible for the conceptual exploration of modular strategies, starting from the application of the joint and elaborating design concepts enabling different configurations aligned with Modularity in Use (MiU) and Modularity in Production (MiP).

The implementation phase followed an iterative workflow combining practical prototyping, digital modeling, and visualization tools. MiD exploration involved 3D modelling, material and process selection, and physical prototyping, while MiU and MiP implications were analyzed through 3D modelling, renderings, and visual communication tools (Adobe Illustrator 2025, Photoshop 2025) to schematize potential usage contexts and production flexibility. This structured interdisciplinary approach resulted in a fully defined design concept proposal, combining an engineering-driven perspective, focused on technical feasibility and product architecture, with a design-oriented perspective addressing functionality, usability, and user-centered requirements.

While the development of the enabling component (joint) was essential to activate modular architecture, the present paper specifically focuses on the design-driven exploration of Modularity in Use (MiU) and Modularity in Production (MiP). The detailed technical development of the joint, including engineering optimization and validation, is therefore outside the scope of this contribution, although it constitutes the enabling condition for the modular configurations discussed in Section 4.3.

4. Results

4.1. Synthesis

This section presents the results emerging from the analytical and design activities. In accordance with the methodological structure outlined in Section 3, the results are organized into two complementary groups: intermediate results, generated during the Inspiration and Ideation phases, and final results, from the Implementation phase.

The first group synthesizes how modularity strategies were identified and classified, across multiple sources and processes. It includes: (i) the construction of a dedicated dataset and the clustering of modularity principles derived from the patent analysis; (ii) the cross-comparison between identified clusters and case studies through Venn-diagram visualizations; and (iii) the reconstruction of the ideation process, showing how analytical insights informed design process.

The second group of results presents the modular concept developed. This concept integrates the defined modular strategies and demonstrates their application through multiple dimensions, including scalability, transportability, electrification, and the structural transformation from a bicycle to a cargo bike configuration.

4.2. Intermediate Results

4.2.1. Dataset Construction and Clustering of Modularity Strategies

The analysis of patent prior art resulted in a dataset of 76 patents related to bicycle and cargo bike modular frames, filtered according to the relevance criteria described in Section 3.2.1. This dataset provided a structured overview of existing modular solutions and allowed the extraction of recurrent principles that can be conceptually linked to Baldwin & Clark's framework: Modularity in Use (MiU), Modularity in Production (MiP), and Modularity in Design (MiD) [48].

Through qualitative analysis of the patents, three functional clusters were identified, representing strategies observed in practice that can be associated with MiU and/or MiP. These clusters do not correspond one-to-one with Baldwin & Clark's theoretical dimensions; rather, they capture recurring strategies of modularity observed in the patents, which may appear individually or coexist within the same vehicle:

- Cluster 1—Modularity for production or end-of-life purposes.
  This cluster includes patents in which modularity is introduced to facilitate assembly, maintenance operations, the replacement of structural sections, or the separation of

materials at end-of-life. Most solutions involve detachable joints, simplified connection systems, or modular subframes designed to support manufacturing processes.

- Cluster 2—Modularity for transport and space-saving storage.
  Patents in this category describe modularity to facilitate transport and optimize storage space. The proposed solutions involve frames that can be disassembled into separate, transportable modules, reducing overall volume for intermodal mobility or storage. Folding bicycles and partially collapsible designs were excluded, focusing only on fully separable modular solutions.
- Cluster 3—Modularity for reconfiguration and functional transformation.
  The third cluster includes patents that exploit modularity to enable structural reorganization of the vehicle, allowing the frame to be reconfigured for different functional purposes. Examples range from gradual adjustments for anthropometric fit or cargo volume adaptation, to more substantial transformations, such as converting a single bicycle into a tandem, a standard bike into a cargo bike, or adapting the frame for inclusive and accessible transport, accommodating people and children.

Below, Figure 2 presents a Venn diagram illustrating the distribution of patents across the three clusters. The diagram highlights both the number of patents uniquely assigned to each cluster and those shared between clusters, providing a visual summary of modularity strategies in the dataset.

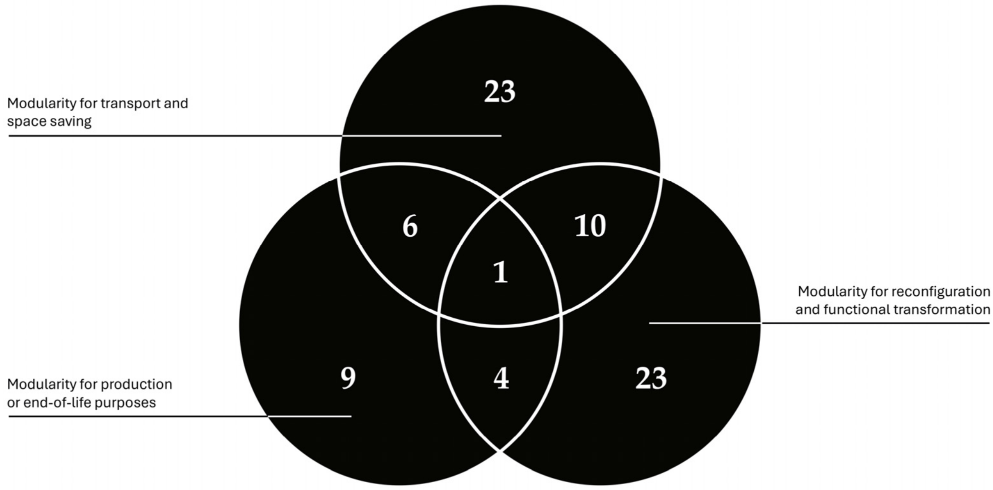


Figure 2. Venn diagram of modularity clusters identified from the patent analysis. Numbers indicate the patents assigned to each cluster (for full references, see Table A4, Appendix B).

In parallel, the dataset captured four primary methods of frame disassembly: (i) slide: longitudinal separation of the frame into two main sections, (ii) pull-out: transversal separation of the frame into two main sections, (iii) split: use of removable structural nodes connecting different frame sections, allowing separation into multiple modules, (iv) add-on: integration of additional elements or modules without modifying/with minimal modification to the core frame structure. These methods are primarily associated with MiD principles and provide concrete examples of how modular design is realized at the technical level.

Each patent in the dataset was systematically associated with its corresponding functional cluster (1, 2 and/or 3) and disassembly method (slide, pull-out, split, add-on). This organization offers a structured overview linking modularity strategies, disassembly techniques, and their practical implementation, forming a solid empirical foundation for subsequent design exploration in ideation and implementation phase.

The full dataset is provided in Table A4, Appendix B.

4.2.2. Case Study Cross-Comparison

Consistent with the heuristic, purposive approach described in Section 3.2.2, a set of 15 products was selected to illustrate the modular strategies derived from the patent analysis.

Figure 3 visualizes the distribution of these products through a Venn diagram, highlighting the overlap and coverage of three clusters.

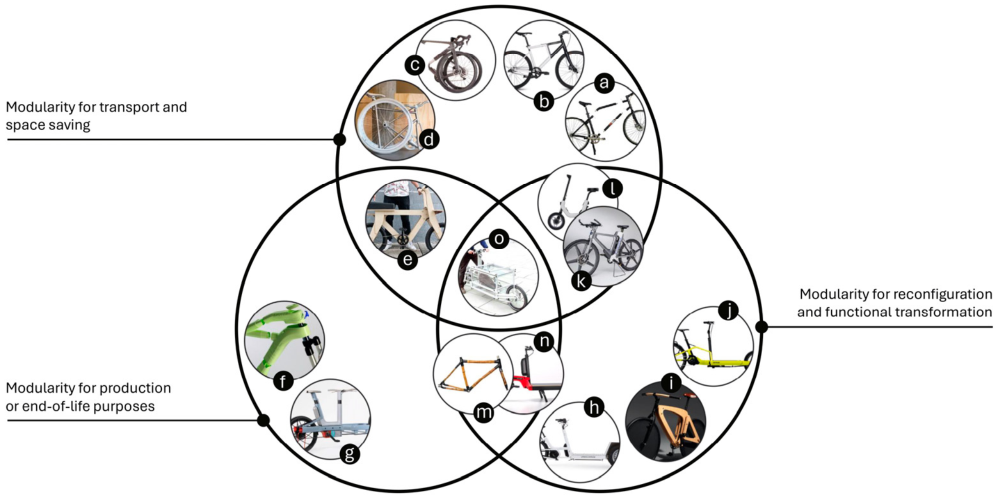


Figure 3. Examples of existing bicycles and cargo bicycles considered in the comparative analysis: (**a**) M-Bike, Unik Innovation [71], (**b**) Krushhausen Cycles [72], (**c**) Landergini bike [73], (**d**) MisterMuratori bike [74], (**e**) Arquimana, Openbike [75], (**f**) Aenimal Bhulk, Eurocompositi [76], (**g**) Lavo, Studiomom [77], (**h**) Tender, Urban Arrow [78], (**i**) The Outlaw bike [79], (**j**) Cargoline, Kettler [80], (**k**) Ford's Mode: Flex bicycle [81], (**l**) Gmigo One, Tianjin Jidian Road Technology Co. [82], (**m**) Bamboocycles [83], (**n**) Heta, Douze cycles [84], (**o**) XYZ Bike [85].

Although not statistically representative, this qualitative sampling [65] provides an immediate and tangible overview of modular strategies in practice, enabling cross-comparison and revealing trends and technological trajectories relevant for the subsequent design exploration.

All clusters identified through the patent analysis are represented in the selected products, confirming the applicability of the modularity strategies. Specifically:

- Cluster 1—Modularity for production or end-of-life purposes.
  Case studies reveal vehicles experimenting with innovative and/or sustainable materials (e.g., wood, composites, high-performance plastics) and advanced manufacturing technologies such as 3D printing. Observed strategies include detachable joints, atypical frame designs based on modular profiles with simplified connection nodes, and layered or assemblable frame architectures rather than traditional tubular constructions.
- Cluster 2—Modularity for transport and space-saving storage.
  Selected vehicles demonstrate fully disassemblable frames for transport and compact storage. Main examples retain standard wheel sizes and are configured for intermodal mobility over medium-to-long distances, distinguishing them from folding bikes, which prioritize compactness over riding performance for first or last mile travels.
- Cluster 3—Modularity for reconfiguration and functional transformation.
  Products in this cluster illustrate modular solutions that enable structural reconfiguration of the frame, predominantly observed in cargo bicycles designed for the transport of goods or multiple passengers.

This cross-validation provides a direct visualization of how modular clusters identified through patent analysis translate into concrete implementations across commercial, research, and conceptual products, clarifying the shift from architectural intent to operational strategies and informing subsequent design ideation.

4.2.3. Ideation Process Visualization

The Inspiration phase was guided by a set of RQ focused primarily on MiD and its potential implications for MiU and MiP (see Section 2.2). The insights generated through this investigation provided the foundation for reframing the inquiry from an analytical to a design-oriented perspective.

Building on this evidence, two specific RQs were formulated, one centered on MiU and one on MiP, to structure and direct the subsequent Ideation phase.

Each research question, reported below, informed a dedicated Design Sprint session:

- RQ-1b (MiU—User-Centered perspective): How can modularity enable reconfigurable bicycle and cargo-bike frames that enhance usability, accessibility, and overall user experience in personal and logistic mobility scenarios, by supporting, for example, intermodal transport, compact storage, adaptation to different riders, and everyday urban travel routines?
- RQ-2b (MiP—Production-Centered perspective): How can modularity support splittable, and easily assemblable frame that streamline production, reduce component variability, and improve maintenance, repair, end-of-life processes, while also simplifying transport and storage throughout manufacturing, distribution, logistics and lifecycle management?

The first Design Sprint session explored how modularity could enhance user adaptability and functional versatility in everyday personal mobility. Storage constraints, combined with the need for supporting multiple mobility scenarios, directed the investigation toward hybrid 2-in-1 solutions.

The focus shifted to modular assemblies in which a limited set of structural modules could be reconfigured into either bicycle or cargo-bike configurations. This approach aimed to minimize storage volume while enabling different functional setups (from commuting to load-oriented scenarios), without requiring users to own or store multiple vehicles. Attention was given to the practicality and intuitiveness of disassembly: concepts tended to favor quick, tool-minimal mechanisms and a reduced number of separable modules. Consequently, most proposals converged toward solutions in which the frame could be split into two main parts, balancing modular flexibility with ease of user interaction (see Figure 4a,b).

The second Design Sprint session shifted the focus to production and assembly, investigating how separable frames could streamline manufacturing by reducing both part-specific machining and final assembly operations.

The exploration led to concepts based on a splittable frame in which the main structural nodes were reinterpreted as modular joints. These joints, conceived as customizable connection elements, enabled geometric variation while keeping the connecting tubes simple, standardized, and easily replaceable. This approach offered several advantages: most transformations were concentrated at the joint level, while independent connector modules facilitated maintenance, repair, size scalability, logistic storage, and end-of-life disassembly (see Figure 4c).

Further reflections highlighted two major technical challenges common to both MiU and MiP oriented solutions: the integration of electric components and the continuity of the rear brake system. Fully detachable frames require strategies to manage battery positioning, motor mounting, and cable routing, as well as mechanisms for preserving or temporarily disconnecting the brake line. These challenges are particularly critical in MiU oriented scenarios, where reconfiguration is performed by the user and therefore requires intuitive, safe, and low-effort interfaces. In MiP oriented configurations, the same issues persist but are mitigated by occurring exclusively during manufacturing and assembly, where additional steps can be standardized more easily.

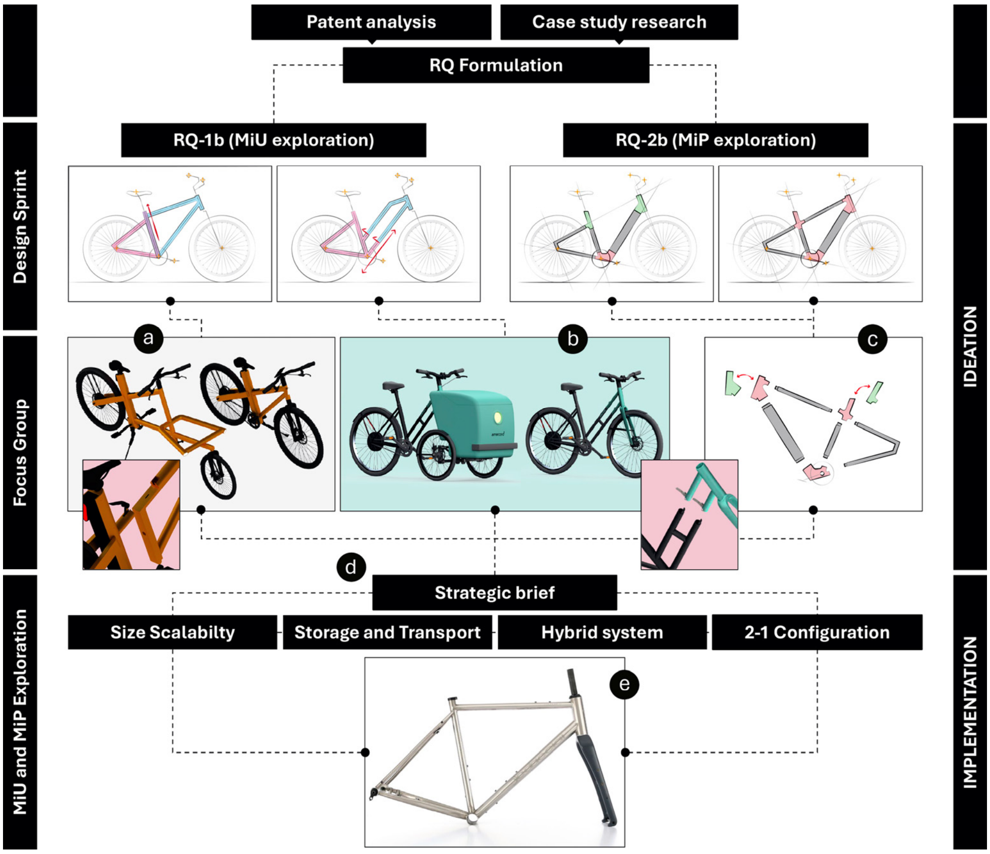


Figure 4. Overview of the co-design process. (**a**) Modular bike with longitudinal frame separation—design by C. Pacini, IDEE Lab; (**b**) Modular bike with transversal frame separation—design by D. R. Ciriano, C. Zingoni, IDEE Lab; (**c**) Modula bike with splittable frame; (**d**) Strategic brief; (**e**) "Polvere titanio" bike reference—Dedacciai Strada, Dedaindustrie S.r.l.

Building on these insights and the subsequent iterative refinement in the focus group, the WP 2.1 research team consolidated the findings into a strategic design brief.

Four priority modularity directions were selected: (i) size scalability, (ii) storage and transportability, (iii) hybrid system bike/e-bike, and (iv) structural transformation between bicycle and cargo-bike configurations. These strategies were applied starting from the study of the reference gravel frame provided by Dedacciai Strada—Dedaindustrie S.r.l. and had to be implemented through simplified and user-friendly detachable frame solutions characterized by: (i) a maximum of three main pieces, (ii) an integrated system for electrification and rear brake transmission, (iii) an interchangeable set of cargo modules (see Figure 4d,e).

4.3. Final Results: An Implemented Modular Frame Concept

4.3.1. Premise

As already described in Sections 3.4 and 3.5, the final modular concept is the outcome of an iterative co-design process structured in two subsequent phases. The first phase was oriented towards the identification of promising modular strategies, while the second phase focused on their implementation and verification through iterative focus groups and technical sessions with WP2.1 (see Section 4.2.3).

This structured workflow provided the foundation for the development of a modular vehicle prototype based on the dimensional and constructional constraints of the reference bicycle frame (Polvere Titanio) supplied by the industrial partner.

The key enabling element of the prototyped modular vehicle is a joint, developed by the University of Bergamo in collaboration with Dedacciai Strada—Dedaindustrie S.r.l. The joint consists of two complementary 3D printed parts with a stepped interface, fastened by a single screw, allowing complete disassembly and reconfiguration of the frame.

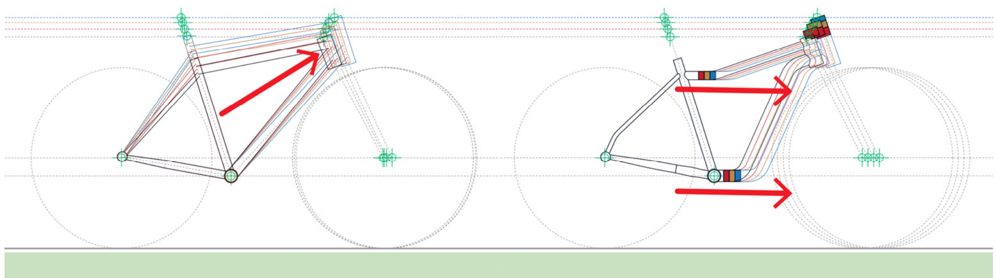
A first full-scale modular frame prototype was manufactured to evaluate the modular interface and structural requirements. The prototype was publicly presented at the "MOST—L'innovazione che unisce" event [86].

In the context of the present work, the prototype operates as an enabling lever that embeds Modularity in Design (MiD) and provides the technical foundation for the design-driven concept exploration of Modularity in Use (MiU) and Modularity in Production (MiP) based on the four strategic directions of the project brief.

4.3.2. Modularity and Scalability

Scalability was explored to extend the frame's adaptability to a broad range of anthropometric profiles while preserving ergonomics and pedaling efficiency.

The investigation began with an in-depth analysis of the Polvere Titanio Ti frame across four sizes (S, M, L, XL). The study revealed that key variations occur in the top and down tubes, in the head tube, and in the seat tube, while wheel positions remain fixed. Specifically, the top and down tubes increase in length, elevating the head tube, and the seat tube extends proportionally (Figure 5a).



(a) (b)

Figure 5. (**a**) Overlay of the four sizes of the "Polvere Titanio" Frame—Scalability across all components. (**b**) Overlay of the four sizes of the project frame—Scalability through horizontal movement and saddle and handlebar regulation.

Based on these findings, a modular sizing strategy was developed to allow growth in specific, controlled directions rather than proportional scaling of all elements. Horizontal adjustability is achieved via translation of the transversal tubes, while vertical adaptability is provided by a telescopic handlebar stem and saddle, standardizing the head tube and column to the medium frame size (Figure 5b).

Three conceptual disassembly strategies were hypothesized to implement size scalability through modularity: (i) Extendable joints, allowing tubular elements to slide and lock continuously at variable lengths; (ii) Multi-point joints, enabling tubes to connect at predefined positions for discrete size settings; (iii) Four-part modular division, in which the rear triangle and front head module remain fixed, while the top and down tubes are swapped to achieve the desired frame size.

4.3.3. Modularity and Transportability

The vehicle was developed to be split into three main modules: front head, top tube, and rear triangle, reducing the volume of the vehicle while preserving structural performance. The three-part assembly was designed to optimize both transport and domestic storage (Figure 6). In particular, detaching the top tube from the head module produces a significant reduction in the footprint of the stored bicycle and aligns with the configuration logic adopted for the 2 in 1 modular solution explored in Section 4.3.5.

Figure 6. Visualization of the three main modules, disassembly scheme and overall dimensions when disassembled.

The joint geometry ensures self-aligning assembly, while the single-screw fastening mechanism enables quick and tool-minimal disassembly. Internal passages within the joint allow the continuity of the rear brake line and the routing of optional electrical connections, enabling the bicycle to be separated in three straightforward steps without disconnecting functional systems.

4.3.4. Modularity from Bike to E-Bike

The final modular frame concept integrates a dedicated electrification strategy that enables a simple transition from a standard bicycle to an e-bike configuration. The design adopts a modular logic in which all electric components are conceived as add-on elements interfacing with the structural frame modules (Figure 7).

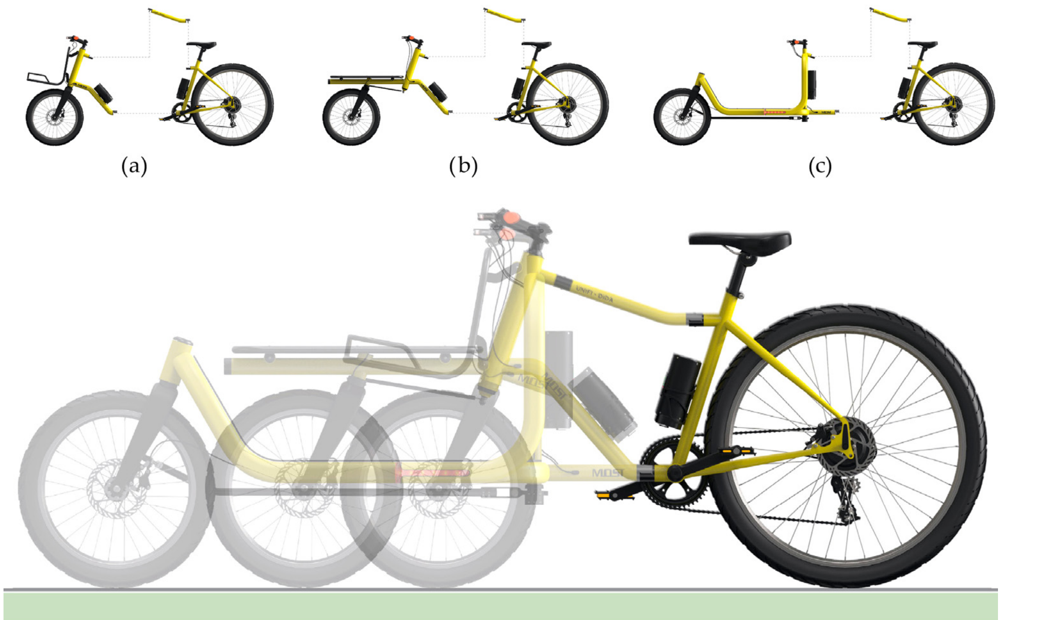
Figure 7. Transition from bike to e-bike by removing rear wheel and adding a modular bottle-battery and a motorized rear wheel.

The electrification system is guaranteed by 3 key elements: (i) modular battery integration, in which the central frame module houses one or two bottle-battery units that can be inserted or removed without permanent fixtures, maintaining full compatibility with the non-electric configuration, (ii) rear hub motor interchangeability, enabled by a rear module designed to accept either a standard or motorized wheel, and (iii) integrated power routing, achieved through plug-in connectors embedded in the modular joints, providing electrical continuity between front controls and the rear motor while keeping the wiring fully internal on the frame.

The same electrification system applies seamlessly to the cargo-bike variants, as the rear module and cross-tube module remain unchanged across configurations, ensuring full compatibility between bike, e-bike, cargo, and e-cargo bike setups.

4.3.5. 2-in-1 Modular Frame: From E-Bike to Cargo Bike

Building on the previously defined modular bike/e-bike frame, the project extended the modular logic to incorporate detachable, transportable, and dimensionally scalable front cargo modules, compatible with the standard rear module containing the rear hub motor and battery housing. Three front cargo modules were developed (Figure 8) to address different load requirements: (i) the small cargo module (Module-S) preserves compactness and maneuverability of the bicycle, integrating a front rack with a 20″ wheel to carry light loads, (ii) the medium cargo module (Module-M) provides a more stable and extended platform positioned on a 20″ wheel, suitable for medium-sized loads, including delivery boxes or compact service equipment, while remaining compatible with standard urban cycling infrastructure, and (iii) the large cargo module (Module-L) maximizes cargo capacity, allowing the accommodation of different types of tailor made boxes for transporting people or goods.



(a) (b) (c)

Figure 8. Visualization of modules and disassembly scheme of the three cargo bike variants: (**a**) Module-S, (**b**) Module-M, (**c**) Module-L.

Each module connects seamlessly with the rear frame and top tube modules, maintaining structural and formal continuity. The modular joint ensures precise mechanical connection, integrated internal routing for rear brake, and electrical continuity, enabling quick assembly and disassembly of the cargo modules in three straightforward steps.

This design supports a 4-in-1 system that allows reconfiguration between standard bike, e-bike, cargo bike, and e-cargo bike configurations using the same base frame, ensuring dimensional scalability, transportability, and electrification.

5. Discussion

5.1. Modularity on a RfD Perspective

The qualitative results from the Inspiration Phase (RfD) (see Sections 4.2.1 and 4.2.2), reveal a structured and multi-dimensional perspective on modularity in light vehicles design. Interpreted through the MiU, MiD and MiP framework [48], the three functional clusters identified in the study illustrate a continuum from production-centered modularity (MiP) to user-centered configurability (MiU).

Cluster 1—Modularity for production or end-of-life purposes is primarily associated with MiP, emphasizing strategies aimed at optimizing manufacturing efficiency, simplifying assembly, facilitating maintenance, and supporting end-of-life management. Within the MiD dimension, this cluster includes detachable joints, modular subframes, and articulated connection systems. The resulting assembly complexity reflects a design focus on production efficiency rather than direct user interaction.

Cluster 2—Modularity for transport and space-saving storage occupies an intermediate position (MiP) and (MiU). From a production perspective, disassemblable frame architectures facilitate logistics, reduce storage volume, and simplify handling along the supply chain. From a user perspective, modular disassembly supports compact storage and intermodal mobility while preserving performance, ergonomics, and structural integrity. Unlike folding bicycles, which often involve trade-offs between compactness and riding performance, fully separable modular designs appear to retain the functional capabilities of standard bicycles. In terms of MiD, production-oriented solutions tend to increase mechanical complexity, whereas user-oriented designs prioritize simplified and intuitive disassembly.

Cluster 3—Modularity for reconfiguration and functional transformation exemplifies MiU, with modularity enabling adaptation to diverse user needs, ranging from ergonomic adjustments to more substantial transformations, such as converting a standard bicycle into a cargo bike or integrating electrification modules. These solutions demonstrate how modular design can address accessibility requirements, multi-purpose transport, and hybrid operational modes, with MiU acting as the primary driver and MiD and MiP serving as enabling layers.

The four identified frame disassembly methods further illustrate the interplay between MiD and MiP/MiU. Split mechanisms are predominantly associated with Cluster 1, supporting production and maintenance-oriented objectives. Slide and pull-out solutions are more common in Cluster 2, particularly when modularity is oriented towards user-centered transport and storage. Add-on configurations, prevalent in Cluster 3, enable flexible functional augmentation, maximizing user agency while maintaining mechanical continuity. This progression illustrates a clear principle of progressive MiD simplification for user interaction from MiP to MiU, aligned with the layered logic of modularity observed across clusters.

Considering potential application domains, modularity may generate value in three areas. In industrial contexts, MiP-oriented strategies can support scalable manufacturing and lifecycle management. In personal mobility, MiU-driven functional transformation enables users to adapt vehicles to diverse commuting, recreational, or storage needs, enhancing accessibility, ergonomics, and flexibility. In professional or operational settings, MiU facilitates fleet reconfiguration, task-specific adaptation, and optimized maintenance, providing versatility for logistics, delivery, and multi-purpose service vehicles.

Overall, these findings reinforce modularity as a layered design principle rather than a singular property, capable of fostering sustainable, versatile, and user-responsive light vehicle solutions, while also supporting scalable production, lifecycle management, and operational efficiency.

5.2. Modularity on a RtD Perspective

The Ideation and Implementation phases (see Sections 4.2.3 and 4.3) translates the insights derived from the Inspiration phase into a set of modular design strategies and their subsequent materialization into a bike frame-level solution.

These phases demonstrate how the modularity clusters identified can be operationalized within a design process, informing concrete architectural and functional decisions.

The four strategic directions explored: scalability, transportability and storage, electrification, and functional transformation embody the continuum of modularity from MiP to MiU discussed through the clusters.

Scalability emerges as a design strategy that can be interpreted through both Modularity in Production (MiP) and Modularity in Use (MiU), although with different degrees of maturity and impact. From an MiP perspective, the use of detachable modules to enable frame size variation suggests a potential alternative to fully welded, size-specific frames offering benefits such as reduced frame variants, component reuse, and increased production flexibility (Cluster 1). However, these benefits remain largely conceptual at this stage, as no quantitative assessment of manufacturing complexity, cost, or structural performance has been included. Thus, scalability should be interpreted as a design potential rather than a validated industrial advantage.

From a MiU perspective, scalability addresses the controlled adaptation of frame dimensions to different anthropometric profiles. Modular joints and interchangeable tubes enable dimensional adjustments that may allow a single vehicle to accommodate users with significantly different body sizes, without relying solely on secondary adjustments (e.g., saddle or stem) (Cluster 3). This approach appears particularly relevant in shared or professional-use contexts, where the same vehicle may be used by multiple riders. Nevertheless, the intuitiveness and safety of such adjustments strongly depend on interface and locking mechanism design, highlighting the critical role of MiD.

The three mechanisms explored for size scalability illustrate a continuum of trade-offs between MiP and MiU: extendable or indexed joints prioritize user interaction but increase mechanical complexity, whereas segmented frames simplify standardization and joint design but require more deliberate intervention for size changes.

Transportability and storage are realized through full frame disassembly into a limited number of primary modules (three modules). This operationalizes the logic of Cluster 2 from a concrete MiU perspective.

The proposed modular solution targets users who prioritize ride quality and structural robustness, accepting disassembly as a deliberate, non-instantaneous action. This distinction identifies a specific user profile: performance-oriented cyclists and multi-modal travelers who value storage flexibility and medium to long distance intermodality without sacrificing ergonomics, handling or ride performance.

At this level, the design exploration highlights one possible trade-off: an increase in interface complexity is accepted to enable frame disassembly, while preserving the overall structural behavior and riding performance. Rather than adopting localized folding mechanisms, the concept explores a system-level modular solution based on separable structural sections. This approach does not aim to replace folding-based strategies but suggests an alternative design direction in which transport-oriented modularity is addressed through controlled disassembly and user-managed interaction, while maintaining the functional integrity of the vehicle.

Electrification is explored as a modular strategy from an MiU perspective. Modular electrification supports user adaptability by enabling different operational modes within the same vehicle architecture (Cluster 3). Components such as the battery and rear motor are conceived as add-ons that interface with the structural frame modules, allowing users to transition between standard bicycle and e-bike configurations. This strategy is particularly relevant for hybrid usage scenarios, where the same vehicle may serve recreational riding, daily commuting, or load-intensive tasks.

At the same time, the modular electrification system highlights the importance of user capability in performing functional transformations. While designed for compatibility and straightforward integration, even simple operations, such as inserting the battery or connecting the rear motor, require some familiarity with mechanical systems. This underscores a critical design consideration: modularity increases versatility, but it also introduces a threshold of user skill. For some users, these operations may be easy and intuitive, whereas for others they could represent a barrier to full use.

The design challenge lies in balancing functional flexibility with intuitive, low-effort interactions, ensuring that modularity enhances usability without relying on specialized knowledge or technical competence.

Functional transformation, operationalized through the 2-in-1 modular vehicle concept, exemplifies the apex of MiU of Cluster 3. This strategy allows a single base frame to accommodate multiple configurations, transitioning from a standard e-bike to an e-cargo bike, and supporting diverse operational scenarios.

The design of three front cargo modules demonstrates the potential for graded adaptability, targeting a spectrum of use cases ranging from personal commuting to professional logistics. The 2-in-1 modular design provides opportunities for fleet-level optimization, allowing rapid reconfiguration to meet variable operational needs, improving distribution efficiency, and enabling tailored business models.

Beyond professional and operational contexts, the concept also highlights opportunities for personal use. The modular cargo solutions allow users to customize the vehicle for daily commuting, shopping, or transporting children while maintaining a compact footprint for storage in limited domestic spaces. This demonstrates that modularity can reconcile versatility with spatial constraints, offering individual users the flexibility to adapt a single vehicle for multiple purposes without the need for multiple bicycles.

Overall, RtD exploration demonstrates that modularity can be operationalized to support both production and user-centered objectives, enabling scalable, transportable, electrifiable, and functionally transformable light vehicles. The iterative integration of MiP, MiU, and MiD perspectives highlights how modular strategies can translate conceptual clusters into practical design solutions that address diverse mobility scenarios and user needs.

6. Conclusions

This study proposed a design-driven framework to investigate modularity as a vector of innovation in bicycles and cargo bikes, integrating systematic insights from patent analysis, qualitative evidence from case studies and operational directions derived from iterative co-design exploration.

The results show that adopting modularity as a strategic design lever unlocks multiple opportunities to innovate within micromobility from a bottom-up perspective. Modularity supports functional flexibility, user-centered adaptation, and production efficiency while enabling systemic improvements that can foster new mobility habits and patterns of use.

Interpreted through Baldwin & Clark's framework, the study further demonstrates that modularity operates as a layered design principle. Starting from Modularity in Design (MiD), it exerts significant influence on both production-oriented (MiP) and user-oriented (MiU) dimensions, highlighting its role beyond a singular structural property.

Tables 2 and 3 summarize the correspondence between the research questions that informed the analytical exploration (RQ1a–RQ4a) and those guiding the design-driven phase (RQ1b–RQ2b), along with the key qualitative insights generated in each stage.

Table 2. Summary of the research questions (see Section 2.2 for the full description) and corresponding insights and results from the analytical phases.

Research Questions [1]	Patent Analysis	Case Studies Research
RQ-1a	- Recurring modular strategies: detachable joints, modular subframes, articulated nodes - Four disassembly modalities: slide, pull-out, split, add-on - Solutions converge toward 2, 3 or multiple part separable frames	- Use of alternative materials (wood, composites, high-performance plastics) enabling new modules typologies - Layered, profile-based or assemblable architectures beyond classic tubular frames
RQ-2a	- Interface complexity and non-intuitive disassembly - Continuity issues for brake lines and electrics in separable frame - Limited anthropometric scalability - Modular personalization predefined "upstream" rather than user-driven	- Reconfiguration mostly constrained to cargo segment; weak diffusion in standard bicycles - Single-scope modularity; rare cross-cluster integration
RQ-3a	- Storage and intermodal transport via separable frames - Functional modularity: cargo, electrification, 2-in-1 systems - Ergonomic adaptability	- Integration of standard wheel sizes in separable frames to retain riding performance - Intermodal, medium-range mobility enabled without sacrificing ergonomics or handling - Cargo modularity expanding beyond simple load carrying
RQ-4a	- Facilitated assembly, maintenance and end-of-life - Standardization of tubes and modular joints for flexible range extension - Reduced fixed product variants through segmented frames - Improved logistics via transportable modules	- Functional adaptations predefined by manufacturer (gamma-based) - Alignment between modular joints and advanced fabrication (3D printing, CNC, etc.) - Potential synergy between material optimization and detachable architectures for circularity

[1] The research questions (RQ-1a, RQ-2a, RQ-3a and RQ-4a) are reported in Section 2.2

Table 3. Summary of the research questions (see Section 4.2.3 for the full description) and corresponding insights and results from design driven phases.

Research Questions [1]	Design Sprint and Iterative Focus Group	Final Concept
RQ-1b	- Limited set of structural modules reconfigurable into bike or cargo bike setups - 2-in-1 modular frame enhances usability, storage, and multi-scenario adaptability - Intuitive, tool-minimal disassembly supports everyday user interaction	- 2-in-1 modular frame allows reconfiguration between bike and cargo bike - Size scalability via modular joint and component - Modular joints with integrated electrification enable intuitive reconfiguration - Low-effort functional transformations for diverse users and mobility scenarios
RQ-2b	- Splittable frame with modular joints enables standardized tubes and connector modules - Simplifies assembly, maintenance, repair, end-of-life handling, and logistics - Most transformations concentrated on joints for efficiency	- Three-module frame with standardized tubes and modular joints enabling scalable frame sizes - Facilitates assembly, maintenance, repair, end-of-life handling, and logistics - Modular electrification and internal routing for vehicle hybrid configurations

[1] The research questions (RQ-1b and RQ-2b) are reported in Section 4.2.3

The study provides a comprehensive qualitative exploration of modular strategies and does not include detailed quantitative assessments of structural performance, materials, or life-cycle impacts. Building on these findings, the main outcome of this research is a basis for a structured strategic framework to guide modular light vehicle design. By combining analytical investigation and iterative design exploration, such a framework can transform theoretical and empirical insights into a systematization of potential modular strategies, enabling informed design decisions that balance production efficiency, adaptability, and user-centered considerations.

The modular prototype developed in collaboration with project partners (WP2.1 at the University of Bergamo and Dedacciai Strada—Dedaindustrie S.r.l.) provided the platform that enabled these exploratory design investigations (see Sections 3.5 and 4.3.1). Future studies could extend this work by conducting detailed quantitative evaluations, structural performance of the joint and the vehicle, materials efficiency, life-cycle assessment, and production considerations, to complement and validate the insights presented here.

Overall, this study demonstrates how a design-driven, bottom-up approach can generate actionable strategies to enhance adaptability, usability, and production efficiency in light vehicles, offering both researchers and practitioners a structured basis for further innovation.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

MOST	National Centre for Sustainable Mobility
PNRR	National Recovery and Resilience Plan
WP2.1	Work Package 2.1
MiP	Modularity in Production
MiD	Modularity in Design
MiU	Modularity in Use
RQ	Research Questions
RfD	Research For Design
RtD	Research Through Design

Appendix A

Appendix A reports the complete search strings used for the patent prior art analysis. The tables document the progressive refinement of the search strategy across the three exploratory steps.

Table A1 shows the initial search string combining the keyword "modular" with broad vehicle-related terms to identify a preliminary core set of patents and characterize the baseline terminology used to describe modularity. The term "cargo bike" was not included as it is inherently represented within the broader category of bicycles.

Table A1. The table lists the first string of exploratory keywords adopted in Step 1—Section 3.2.1.

Search String [1] **("Modular" + "Vehicle Name")**
Modular* Bike or Modular* Bicycle or Modular* cycle or Modular* electric bike or Modular* electric bicycle or Modular* electric cycle or Modular* e-bike or Modular* e-bicycle or Modular* e-cycle or Modular* ebike or Modular* ebicycle or Modular* ecycle or Modular* pedal assisted bike or Modular* pedal assisted bicycle or Modular* pedal assisted cycle

[1] Search conducted on patents documents published between January 1990 and June 2024, applying filters to keywords appearing in the title and abstract only.

Table A2 reports the second search step, in which modularity-related adjectives were grouped and combined with vehicle related terms as two separate clusters. This broader clustering strategy was designed to expand lexical coverage and capture semantic variations.

Table A2. The table lists the set of modularity-related keywords adopted in Step 2—Section 3.2.1.

Search String [1] **("Adjective") and ("Vehicle Name")**
Detach* or Demount* or Dismount* or Remov* or divis* or Divid* or Splitt* or Disassembl* And Bike or Bicycle or Cycle or Electric bike or Electric bicycle or Electric cycle or e-bike or e-bicycle or e-cycle or ebike or ebicycle or ecycle or Pedal assisted bike or Pedal assisted bicycle or Pedal assisted cycle

[1] Search conducted on patents documents published between January 1990 and June 2024, applying filters to keywords appearing in the title and abstract only.

Table A3 shows the refined search strings used in Step 3, where each adjective was individually paired with each vehicle term to reduce off-topic results and isolate descriptors more closely associated with structural disassembly and modular configurations.

Table A3. The table lists the set of modularity-related keywords adopted in Step 3—Section 3.2.1.

Search String [1] **("Adjective" + "Vehicle Name")**
Detach* Bike or Detach* Bicycle or Detach* cycle or Detach* electric bike or Detach* electric bicycle or Detach* electric cycle or Detach* e-bike or Detach* e-bicycle or Detach* e-cycle or Detach* ebike or Detach* ebicycle or Detach* ecycle or Detach* pedal assisted bike or Detach* pedal assisted bicycle or Detach* pedal assisted cycle
Demount* Bike or Demount* Bicycle or Demount* cycle or Demount* electric bike or Demount* electric bicycle or Demount* electric cycle or Demount* e-bike or Demount* e-bicycle or Demount* e-cycle or Demount* ebike or Demount* ebicycle or Demount* ecycle or Demount* pedal assisted bike or Demount* pedal assisted bicycle or Demount* pedal assisted cycle
Dismount* Bike or Dismount* Bicycle or Dismount* cycle or Dismount* electric bike or Dismount* electric bicycle or Dismount* electric cycle or Dismount* e-bike or Dismount* e-bicycle or Dismount* e-cycle or Dismount* ebike or Dismount* ebicycle or Dismount* ecycle or Dismount* pedal assisted bike or Dismount* pedal assisted bicycle or Dismount* pedal assisted cycle
Remov* Bike or Remov* Bicycle or Remov* cycle or Remov* electric bike or Remov* electric bicycle or Remov* electric cycle or Remov* e-bike or Remov* e-bicycle or Remov* e-cycle or Remov* ebike or Remov* ebicycle or Remov* ecycle or Remov* pedal assisted bike or Remov* pedal assisted bicycle or Remov* pedal assisted cycle
Divis* bike or Divis* bicycle or Divis* cycle or Divis* electric bike or Divis* electric bicycle or Divis* electric cycle or Divis* e-bike or Divis* e-bicycle or Divis* e-cycle or Divis* ebike or Divis* ebicycle or Divis* ecycle or Divis* pedal assisted bike or Divis* pedal assisted bicycle or Divis* pedal assisted cycle
Divid* Bike or Divid* Bicycle or Divid* cycle or Divid* electric bike or Divid* electric bicycle or Divid* electric cycle or Divid* e-bike or Divid* e-bicycle or Divid* e-cycle or Divid* ebike or Divid* ebicycle or Divid* ecycle or Divid* pedal assisted bike or Divid* pedal assisted bicycle or Divid* pedal assisted cycle
splitt* Bike or splitt* Bicycle or splitt* cycle or splitt* electric bike or splitt* electric bicycle or splitt* electric cycle or splitt* e-bike or splitt* e-bicycle or splitt* e-cycle or splitt* ebike or splitt* ebicycle or splitt* ecycle or splitt* pedal assisted bike or splitt* pedal assisted bicycle or splitt* pedal assisted cycle
Disassembl* Bike or Disassembl* Bicycle or Disassembl* cycle or Disassembl* electric bike or Disassembl* electric bicycle or Disassembl* electric cycle or Disassembl* e-bike or Disassembl* e-bicycle or Disassembl* e-cycle or Disassembl* ebike or Disassembl* ebicycle or Disassembl* ecycle or Disassembl* pedal assisted bike or Disassembl* pedal assisted bicycle or Disassembl* pedal assisted cycle

[1] Search conducted on patents documents published between January 1990 and June 2024, applying filters to keywords appearing in the title and abstract only.

Appendix B

Appendix B presents the patent dataset developed in this study (see Section 4.2.1).

Table A4. The Dataset reports patent names and references, their correspondence to the three modularity clusters, and the associated frame disassembly method.

Patent Title	**References**	**Production and End-Life Purpose**	**Transport and Space-Saving Storage**	**Reconfiguration and Functional Transformation**	**Disassembly Methods** [1]
Bicycle	[87]	X			Sp
Bicycle	[88]			X	Ao

Table A4. *Cont.*

Patent Title	**References**	**Production and End-Life Purpose**	**Transport and Space-Saving Storage**	**Reconfiguration and Functional Transformation**	**Disassembly Methods** [1]
Bicycle frame	[89]		X		Po, Sl
Bike frame 143	[90]	X	X		Sp
Bike with adjustable size	[91]			X	Sl
Break apart bicycle	[92]	X	X		Sp
Can adjust children bike frame of automobile body length	[93]			X	Sl
Connectable bicycle	[94]			X	Ao
Convertible bicycle	[95]			X	Sp, Ao
Creative mix bicycle	[96]			X	Ao
Cubic meter shrinkable and detachable bicycle rack	[97]		X		Po, Sl
Demountable type bicycle for single or two people riding	[98]			X	Sp, Ao
Detachable and portable bicycle	[99]		X		Po
Detachable bicycle	[100]		X	X	Sp, Ao
Detachable bicycle	[101]		X		Sl
Detachable bicycle based on mortise and tenon joint structure	[102]	X	X		Sp
Detachable bicycle frame	[103]		X		Sl
Detachable bicycle frame	[104]	X			Sp
Detachable bicycle frame	[105]		X		Sl
Detachable bicycle frame	[106]		X		Sl, Po
Detachable bicycle frame and stand pipe integrated battery pack	[107]	X		X	Sp
Detachable bicycle frame suitable for multiple ages of children	[108]			X	Sl
Detachable bicycle with restricted clearance handlebar and pedals	[109]		X		Sl
Detachable bicycle frame “wirebike3”	[110]	X		X	Sp
Detachable combined bicycle	[111]		X	X	Sl, Sp
Detachable electric bicycle frame and electric bicycle	[112]			X	Sp, Ao
Detachable frame and detachable bicycle	[113]	X		X	Sp, Sl
Detachable modularized bicycle frame	[114]		X	X	Po, Ao
Detachable mountain bike	[115]	X	X		Sl
Detachable bicycle with linear type support	[116]		X		Sl
Detachable bicycle with triumph support	[117]		X		Sl
Disassemblable bicycle and disassemblable bicycle frame	[118]		X		Sp

Table A4. *Cont.*

Patent Title	References	Production and End-Life Purpose	Transport and Space-Saving Storage	Reconfiguration and Functional Transformation	Disassembly Methods [1]
Disassembling type bicycle frame	[119]		X		Sl
Disassembly and assembly type bike	[120]		X		Sp
Dismountable bicycle	[121]	X	X		Sp
Dismountable bicycle frame structure	[122]	X			Sp
Dividable bicycle	[123]		X		Sl, Po
Dividable bicycle with a frame made from light-alloy or plastic die casting	[124]	X	X		Sl, Po
Divisible bicycle	[125]		X		Sl
Divisible bicycle frame with connecting device releasably joining two parts	[126]		X		Po, Sl
Foldable jointed bicycle	[127]		X		Sp
Framework, in particular for a detachable Bicycle	[128]	X	X	X	Sp, Ao
Mechanism that plugs into of modularization frame	[129]		X	X	Sp, Sl, Ao
Method for dismantling bicycle	[130]		X		Sp
Modified demountable type bicycle	[131]	X			Sp
Modular bicycle	[132]		X	X	Sp, Po, Ao
Modular bicycle	[133]			X	Sp, Ao
Modular bicycle	[134]			X	Sp, Ao
Modular bicycle	[135]			X	Ao
Modular bicycle	[136]	X			Split
Modular bicycle designs	[137]			X	Ao
Modular bicycle for one or more persons	[138]		X	X	Sl, Ao
Modular bicycle structure capable of realizing longitudinal splicing and longitudinal splicing method thereof	[139]			X	Ao
Modular bicycle structure capable of realizing transverse splicing and transverse splicing method thereof	[140]			X	Ao
Modular Biking Device	[141]	X		X	Sp, Ao
Modular frame for bicycle	[142]	X			Sp
Modular dismountable bicycle	[143]		X		Sp
Modularized detachable bicycle	[144]			X	Sl
Multi-turning-point detachable bicycle frame structure	[145]		X		Sp
Plate-type detachable bicycle and splicing module of bicycle frame of plate-type detachable bicycle	[146]	X			Sp
Quick connect coupling for splittable bicycle frames	[147]		X	X	Sl, Ao

Table A4. *Cont.*

Patent Title	References	Production and End-Life Purpose	Transport and Space-Saving Storage	Reconfiguration and Functional Transformation	Disassembly Methods [1]
Recycling method for bicycle	[148]		X	X	Sl, Ao
Removable bicycle carrier	[149]		X	X	Sl, Ao
Sectional bicycle	[150]		X		Sp, Sl, Po
Shrinkage and removable bike for wheelchair driving assistance	[151]			X	Ao
Simple and dismountable bicycle frame structure	[152]	X	X		Sp
Single-piece mountable/dismountable bike frame structure	[153]		X		Sp, Sl
Split detachable bicycle frame	[154]		X	X	Sp, Ao
Structural improvement of detachable bicycle frame with reduced volume	[155]		X		Sl, Po
Sub chair construction bar for bicycle	[156]			X	Ao
Telescopic bicycle frame	[157]			X	Sl
Three-wheel vehicle or four-wheel vehicle in which front wheel portion and rear wheel portion are detachable	[158]			X	Sl, Po, Ao
Transformable bicycle apparatus	[159]			X	Sp
Transporting device for bicycle to transport infants or adult sitting in seat pushed by cyclist, has shape fixation system obtaining hooking points in front of frame of bicycle along horizontal axle and articulation for monitoring relief	[160]			X	Ao
Tubular detachable bicycle and double-tube bicycle frame	[161]	X			Sp
Two-wheel steering device of detachable bicycle	[162]			X	Ao

[1] Legend Disassembly methods: Slide (Sl), Pull-out (Po), Split (Sp), Add-on (Ao).

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