Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 119 (2023) 302–308

www.elsevier.com/locate/procedia

33rd CIRP Design Conference

# Design for Reliability and Total Cost of Ownership: the case of electric micromobility

Heiner Hans Heimes[a], Achim Kampker[a], Mario Kehrer[a], Jonathan Gerz[a,*], Rafael Marzolla[b], Eduardo Zancul[a,b]

[a]RWTH Aachen University, Production Engineering of E-Mobility Components (PEM), Bohr, 12, Aachen, 52072, Germany
[b]University of São Paulo, Polytechnic School, Production Engineering Department, Av. Prof. Luciano Gualberto, 1380, São Paulo (SP), 05508-010, Brazil

* Corresponding author. Tel.: +49 -0-160-4842775. *E-mail address:* j.gerz@pem.rwth-aachen.de

**Abstract**

Micromobility solutions have been increasingly adopted in cities worldwide. Shared micromobility implementations indicated the need to improve solution design to address the critical issues of product reliability and Total Cost of Ownership (TCO). This work aims to systematize an approach for Design for Reliability (DfR) linked to TCO applied to developing electric micromobility solutions. The research combined a synthesis of the extant literature and an in-depth case study. The case describes how DfR interplayed with TCO to guide solution evolution over product generations. Results include the systematized approach, the case description, and the identification of design research opportunities on micromobility.



*Keywords:* Shared micromobility; Product-Service System (PSS); Pedelec; Electric bicycle; Integrated design approach

## 1. Introduction

The need to reduce greenhouse gas emissions and technological advancements have driven the development of new solutions for micromobility, such as electric bicycles and scooters [1–3] and sharing product-service business models [4].

However, as an emerging segment, several challenges arose, including the need to substantially increase product durability, prevent theft and vandalism, and improve user safety [3]. Another issue for shared micromobility systems' economic viability is reducing the Total Cost of Ownership (TCO) over the product lifecycle. In order to deal with these challenges, vehicle manufacturers and micromobility operators have been directing resources for research and development and vehicle design [3]. Chang et al. [3] expect "*significant improvement in microvehicle durability as well as innovation in microvehicle design and sharing models*".

This work is motivated by the critical role played by product reliability and TCO for shared micromobility systems and the lack of studies combining these two approaches. Design for Reliability (DfR) and TCO concepts are well-developed in the literature [e.g. 5,6]. Still, there is room to advance the link between DfR and TCO and its application to electric micromobility solutions. Moreover, this work is motivated by the opportunities posed by micromobility for generating design research insights. The high degree of novelty, the accelerated market adoption, the proximity to end-users, and the intrinsic tradeoffs position electric micromobility in an interesting setting to be analyzed from the design research theoretical perspective. In this context, the following research question has been defined to lead the research effort: how can Design for Reliability and Total Cost of Ownership be combined to direct product design improvement efforts in electric micromobility? Consequently, this work aims to systematize an approach for


10.1016/j.procir.2023.02.137

Design for Reliability linked to the Total Cost of Ownership applied to developing electric micromobility solutions.

The research method combined a review of the extant literature and data gathering from an in-depth case study conducted on a provider of shared electric bicycle solutions. The case study provides empirical evidence and details how DfR has been combined with TCO analysis to guide the solution evolution over three product generations.

The remainder of the paper is structured as follows. Section 2 presents the literature background on DfR, TCO, and micromobility. Section 3 details the research method. Section 4 presents the analysis and results. The theoretical and practical implications are discussed in Section 5. Finally, Section 6 summarizes the main conclusions and provides directions for further research opportunities in electric micromobility design.

## 2. Literature background

This section summarizes the literature on DfR and TCO, explores the intersection between both topics, and outlines the relevant aspects of micromobility and electric bicycles. A synthesis of the literature summarizes the theoretical foundations for this research.

### *2.1. Design for Reliability (DfR)*

Reliability can be defined as the "*probability that a component, device, system or process will perform its intended function without failure for a given time when operated correctly in a specified environment*" [7]. Considering this definition and the results of a bibliometric analysis with fifty publications, Paganin and Borsato [5] define Design for Reliability as "*a process that describes the entire set of tools that supports the effort to improve the reliability of a product from its conceptual level until its obsolescence*".

Design for Reliability should be applied from the early product development stages, and its perspective encompasses the whole product lifecycle [5]. Although DfR is not a novel approach, comprehensive methodological descriptions of DfR are scarce in the literature. Most publications deal with specific applications [5]. Nevertheless, some activities are frequently present in several DfR applications [5,8–10]: systematizing reliability data collection from the field, understanding end-user solution usage conditions, identifying reliability issues, planning improvement goals, applying design methods and tools, analyzing planned reliability, integrating measures with suppliers and the manufacturing value chain, and monitoring the results. Silverman and Kleyner [9] have identified six typical steps of a DfR program: 1. Identify, 2. Design, 3. Analyze, 4. Verify, 5. Validate, 6. Monitor and Control. Methods and tools applied in DfR efforts are broad, ranging from classic quality-oriented methods, such as Quality Function Deployment (QFD) and Failure Mode and Effect Analysis (FMEA), to digital simulation [5,9].

### *2.2. Total Cost of Ownership (TCO)*

Total Cost of Ownership is an approach for analyzing the costs involved in the acquisition and ownership of a specific product throughout its entire lifecycle, regarding acquisition, use, maintenance, and disposal [6].

The items considered in typical TCO analysis cover a broad range of cost factors, including acquisition, operation (e.g. energy consumption), maintenance (e.g. spare parts, labor), taxes, insurance, and resale or residual value [11–13]. The relevance of each cost factor varies according to the specific sector and solution being analyzed.

Recently, TCO has been increasingly applied to electric mobility to compare alternative technological solutions in different contexts. Palmer et al. [11] assessed TCO for conventional, Hybrid, Plug-in Hybrid, and Battery Electric Vehicles in three countries (UK, USA, and Japan). The authors indicate that TCO is related to market adoption and market share. Patil et al. [12] compared the TCO between Electric Two-Wheelers and Motorized Two-Wheelers in the Indian market considering various product segments and usage profiles. Guo et al. [13] analyzed the TCO for Electric Vehicles and Internal Combustion Engine Vehicles for 17 car segments across short- and long-term ownership periods in the Irish market. Korzilius et al. [14] have applied TCO (focused on component and operation cost) to optimize the design of the electric powertrain of an electric scooter.

TCO has been particularly relevant in the electric mobility sector, as electric mobility solutions compete with established technologies, and cost plays a significant role in user acceptance. Moreover, the existing studies demonstrate a trend to conduct regionalized TCO analysis [11–13], as cost factors (e.g. labor, taxes, incentives) and product usage patterns may vary across regions. TCO also plays a relevant role in servitization [15]. Product-Service Systems (PSS) offer comprehensive solutions typically based on physical products and including value-added services. PSS alters from selling the physical product to alternative business models, such as pay-per-use and subscription models, which micromobility providers commonly apply. PSS models generally aim to decrease the environmental impact, reduce the TCO, and create value for the involved players [15,16].

In specific PSS business models (e.g. pay per use), economic analysis should consider that product unavailability (for instance, due to maintenance) and lower than estimated product lifespan directly impact revenue generation potential and, therefore, business viability.

### *2.3. Relationship between Design for Reliability and Total Cost of Ownership*

Design for Reliability application results in measures to enhance the product design and reduce product faults. In this way, DfR directly influences the Total Cost of Ownership [17]. Although there is a direct relationship between DfR and TCO, studies that combine both approaches are scarce in the literature. One exception is the work by Waghmode and Patil [7], who analyzed the influence of reliability measures on TCO for a band saw cutting machine manufactured and used in India.

The lack of studies combining DfR and TCO indicates that the relationship between both approaches has been overlooked. The reasons may result from the fact the concepts in question have different origins. While DfR stems from the Quality

Management theoretical stream [5], TCO comes from the Purchasing and Management literature [6]. Reliability and TCO play a major role in the electric micromobility industry. Thus, this sector may present a favorable setting for integrating both concepts.

### *2.4. Micromobility and electric bicycles*

Large cities worldwide have seen the rise and widespread adoption of novel transportation solutions conceptualized for shorter distances in urban areas, such as electric bicycles and scooters. These new solutions have been termed micromobility. Micromobility is defined as the application of "*any small, low-speed, human or electric-powered transportation device, including bicycles, scooters, electric-assist bicycles (e-bikes), electric scooters (e-scooters), and other small, lightweight, wheeled conveyances*" [18]. In more specific terms, the Society of Automotive Engineers (SAE) presents a Taxonomy & Classification of Powered Micromobility Vehicles (SAE J3194), which focuses on vehicles that are designed for human transport and excludes solely human-powered vehicles [19]. SAE J3194 delimits micromobility to fully or partially-powered vehicles with a maximum curb weight of 227 kg and a top speed of 48 km/h [19]. The most common vehicles in this category are electric-powered (standing or seated) scooters and electric bicycles (e-bikes). In the European market, pedal electric bicycles (pedelec) are the dominant electric bicycle technology. In the course of this analysis, pedelecs are also referred to as e-bikes.

Micromobility solutions are offered in various forms to end users. Products can be privately owned, meaning that the products are sold to individual users or shared by product-service solution platforms. Sharing systems can be either docked – in which vehicles are positioned in fixed docking stations – or dockless – whereas vehicles do not have predefined parking stations [20–22].

This research focuses particularly on e-bikes in sharing business models. One of the central technologies of e-bikes product structure is the electric powertrain, comprising the battery, the electric motor, and the transmission on the component level. Moreover, e-bikes on sharing systems have GPS location and internet connectivity features. Although micromobility solutions have been experiencing widespread adoption, system providers face relevant challenges. First product generations were initially not designed for the intense year-round outdoor use and misuse typical of sharing systems, resulting in high levels of faults and low lifespan. Since then, new generations of products have aimed to improve reliability, prevent theft and vandalism and improve user safety. Nevertheless, increasing product reliability and reducing TCO remains among the main challenges of the micromobility sector [3]. Beyond costs, improving reliability is also needed to reduce the environmental impact of the products, as in the case of e-scooters [23].

### *2.5. Synthesis of the literature*

The analysis of the literature indicated that micromobility faces the challenge of increasing product reliability while at the same time reducing the TCO. The TCO perspective has been applied consistently in analyzing alternative electric mobility solutions and Product-Service Systems. TCO can be positively impacted by DfR measures that result in increased reliability. However, a lack of studies combining DfR and TCO indicates that the relationship between both approaches has not yet received the potential attention. As an emergent sector experiencing rapid growth with specific challenges, micromobility may offer an interesting ground for design research.

## 3. Method

This study followed a case-based approach [24]. A case study approach is considered suitable for exploring new research areas or providing freshness to an already researched topic [25]. Although the literature about DfR and TCO is well-established, the intersection between both topics is underdeveloped. Moreover, micromobility is an emergent sector posing interesting conditions for generating new insights.

A theoretical case sample was preferred to provide relevant information on the topic [25]. The selected case is an e-bike sharing provider operating in a docked system model since 2014. The case was selected because it displays the phenomenon under consideration. The selected provider promoted the improvement of the e-bikes design over three product generations focusing on enhancing reliability and reducing TCO. The selected case also has proximity to the authors, which is usually favorable to facilitate access to detailed information. One of the current research co-authors was formerly a technical manager at the studied provider.

Data gathering considered multiple sources of evidence, including primary and secondary sources. Data about maintenance occurrences of two software systems employed along different periods were analyzed to identify the most frequent issues for each product generation. Document assessment combined internal and external documents to identify the prioritized product design changes over time. The assessed documents included the internal Product Specification Sheet and publicly available information, such as press coverage about solution updates in the market. Moreover, the former technical manager produced a technical report to document his knowledge about the product design evolution and the design approach applied. Semi-structured interviews were conducted with the current technical experts to understand the design practices and clarify details on the product evolution. The gathered data were triangulated and related to the literature to derive the findings following an inductive approach.

## 4. Analysis and results

This section presents the case study context, the data analysis results, and the underlying design approach combining DfR and TCO to prioritize design changes and guide solution evolution.

### *4.1. Case study context*

The studied case company is a provider of shared e-bike micromobility solutions. The company was established in 2014 and operates on two levels. A parent company provides its end-to-end solutions for companies, municipalities, and other operators interested in deploying e-bike systems. For each town and municipality, a subsidiary company may be founded, which operates the local e-bike sharing system. The unit of analysis is the parent company. Currently, solutions provided by the case company are used in 6 cities in 2 European countries, which implemented more than 200 docking stations with six or more slots each and approximately 1500 e-bikes.

Besides the physical infrastructure composed of e-bikes and docking stations, the solution also comprises a backend and a mobile app for end-users. The backend controls the entire sharing process. This is where the physical assets are managed, the user data is stored, and the sharing transactions are executed up to invoicing. The app allows users to locate docking stations, book e-bikes (within 15 minutes before use), unlock e-bikes, and access usage reports. The solution is provided as pay-per-use (every 30 minutes) and subscription (monthly, annual) business models.

Despite being positioned as a sharing solution provider, the case company also has strong roots and participation in the solution design. The company team developed its first generation of e-bikes resulting in a spin-off from a broader electric mobility group. The docking station was also designed internally by the case company team in partnership with research institutes.

### *4.2. Data analysis*

The data analysis comprised understanding the product evolution and identifying the underlying design pattern in practice in the company case. The product analysis focused on e-bikes, which evolved over three product generations. The docking stations also have had incremental design improvements over time, but the e-bikes were more relevant for reliability and cost, which are the focus of this study.

E-bikes' main modules and components are the frame, the battery, the motor, the wheelsets, the standard bicycle add-on components, and the sharing system specific add-on components. The frame design differs significantly from frames designed for the private segment regarding integration potential and attachment points. In terms of costs, the most expensive components are the motor, including the controller and wire harness (approximately 25-30% of the product cost), battery (approximately 20-25% of the product cost), and frame (approximately 12-15% of the product cost).

Tracking product faults is fundamental for reliability analysis. Therefore, as of operation started, the case company deployed an in-house developed software to track e-bike maintenance occurrences. A commercially available software solution substituted the in-house software four years later. The analysis of a sample of the maintenance records for the first two product generations indicates the most frequent technical problems. The analysis was performed based on a keyword search on the records of the first employed maintenance management software followed by faults classification by predefined categories. According to the analyzed sample, the first e-bike generation mainly faced battery, docking mandrel, and wheel damage. These could be partially attributed to the very intensive use of the shared system in public spaces. The second e-bike generation mainly faced docking mandrel and battery problems, whereas the participation of battery in researched maintenance records was significantly reduced (Fig. 1). The total number of maintenance records was considerably reduced from the first to the second generation. The third generation has been introduced recently, and fault data is still limited.

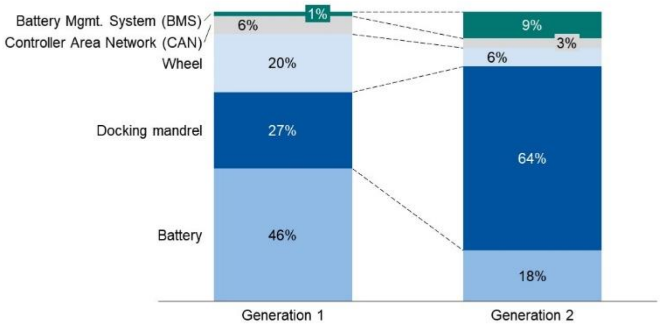


Fig. 1. Most frequent maintenance events by each product generation – sample (source: maintenance databank)

Beyond the maintenance data, the operation allowed the company to acquire quantitative and qualitative data about product usage in the field and better understand product usage patterns. Maintenance data and usage data were combined to guide the product design improvement over three generations of e-bikes. Figure 2 presents a summary of the product generations and the main relevant design improvements. The second generation, introduced in 2019, displayed improved battery encapsulation and housing and improved routing of cables and wires. These two improvements directly addressed recurrent issues from the previous design. The design was also defined to be more compact to facilitate transport, contributing to reduce operation costs (lower TCO) while moving bikes between docking stations to balance availability during the day. The third generation, introduced in 2022, included more advanced IoT functions that also support operation by remote fault diagnosis and troubleshooting. This generation explored increased encapsulation of sub-component, which was defined to optimize the higher reliability with the resulting maintenance effort. The third design generation also improved wheels and tires to reduce maintenance occurrences dramatically.

Over the product generations, the requirements specification sheet played an important function in documenting learnings from reliability analysis and user needs understanding. The analysis of the specification sheet brings relevant insights. For instance, it indicates the need to combine facilitated access for maintenance procedures and theft protection, which is crucial for shared solutions in public spaces. An excerpt of the document illustrates: *"In addition, the holder should provide anti-theft protection and should still be easily dismantled by a technician using a special tool, if necessary"*. Design requirements included a high degree of components integration (e.g. *"The cable routing can be integrated in the frame or mounted externally. When integrated into the frame, sufficient accessibility for maintenance should be ensured"*). Operational knowledge accumulated over time allowed usage requirements to be refined in the requirements specification, including expected mileage for the product lifecycle. The most recent release of the requirement specification document emphasizes the importance of TCO reduction (e.g. *"The minimisation of TCO is the single most important goal"*) as a result of design measures that increase reliability, reduce maintenance efforts and increase solution availability.

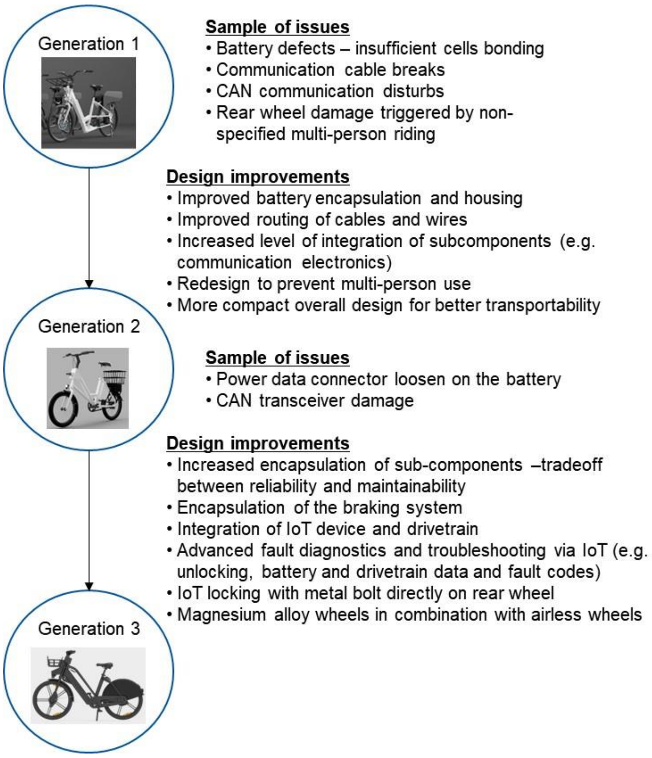


Fig. 2. Prioritized design measures along product generations

Alternative design solutions were assessed and analyzed applying Fuzzy VIKOR multicriteria decision analysis considering technical, business and usability criteria. Therefore, a specific analysis tool was developed internally. When needed, prototypes were provided for usability and durability tests.

As the e-bikes market matured and e-bikes manufacturers developed, the role of the case company in product design also evolved to concentrate on the requirements specification and definition of custom design needs. The case company team developed its first e-bike generation as a spin-off from a broader electric mobility group. The second generation was jointly designed with a contract manufacturer following the case company's requirements, with the case company having a relevant role in the design. The third generation is based on an existing solution adapted to fulfill the case company's specific design requirements. Despite role evolution, the case company kept a central and active role in the design of all product generations. This can be attributed to the deep technical root of its team. None of the product generations were simply sourced from external parties.

### 4.3. Underlying combined DfR – TCO approach

The critical importance of reliability and TCO for the shared e-bike operation led the studied case company to closely combine these elements in the design evolution efforts.

In the studied case, every product fault was documented and recorded in a fault database. Most severe and frequent faults were prioritized. Corrective measures were adopted to solve the problems in the field fleet in the short term. In parallel, design measures were considered for the forthcoming product generation. Design improvement measures were prioritized according to their impact on reducing TCO, even if they resulted in higher acquisition costs (e.g. magnesium alloy wheels and advanced IoT). Beyond facilitating maintenance (e.g. less battery and tire faults) and operation (e.g. design size appropriate for transport), special attention was given to guaranteeing higher availability and extending product lifespan, which also positively impacts sustainability.

The cost model is based on the perspective of the e-bike shared service provider and considers that there is an e-bike fleet for each design generation. The cost model expresses the annual average Total Cost of Ownership of an e-bike of a specific generation (g):

$$TCO_{yr,g} = \frac{\frac{\sum_{n}^{m} AC_g}{Durability_g} + MC_{yr,g} + OC_{yr,g} + EC_{yr,g}}{Fleet_g}$$

where:

- $TCO_{yr,g}$ is the average total cost of ownership in the year yr of operation of a generation g e-bike;
- n, m = sequential first and last e-bike ID in a generation g;
- $AC_g$ = Acquisition Cost = e-bike unit acquisition price + taxes for a generation g e-bike;
- $Durability_g$ = estimated average service lifespan (in years) for a generation g e-bike;
- $MC_{yr,g}$ = Maintenance Costs (annual, generation g) = spare parts (including eventual battery replacements) + maintenance labor costs + maintenance overheads;
- $OC_{yr,g}$ = Operations Costs (annual, generation g) = mobile communications cost + docking station operation cost (e.g. cleaning) + vehicle redistribution + IoT & backend fees + insurance;
- $EC_{yr,g}$ = Energy Costs (annual, generation g) = energy price ($/kWh) * total annual distance traveled (km) * energy efficiency (kWh/km);
- $Fleet_g$ = number of e-bikes from generation g (ID n to m).

The durability was preferred to the depreciation rate as micromobility shared models experience has shown reduced durability due to intensive use and misuse. Resale price and residual value were not considered as the e-bikes are not commercialized after the service lifespan. Instead, parts of out-of-service e-bikes may be refurbished and reutilized as spare parts.

Figure 3 illustrates the combined DfR – TCO design approach that emerged from the analysis of the studied case. The light grey boxes delimit the scope of the approach. The dark grey numbered boxes (1. Identify, 2. Design, 3. Analyze, 4. Verify, 5. Validate, 6. Monitor and Control) illustrate the correspondence to the typical DfR steps (see Section 2.1). The white boxes represent short-term corrective actions and are out of the scope of the structured DfR – TCO approach workflow.

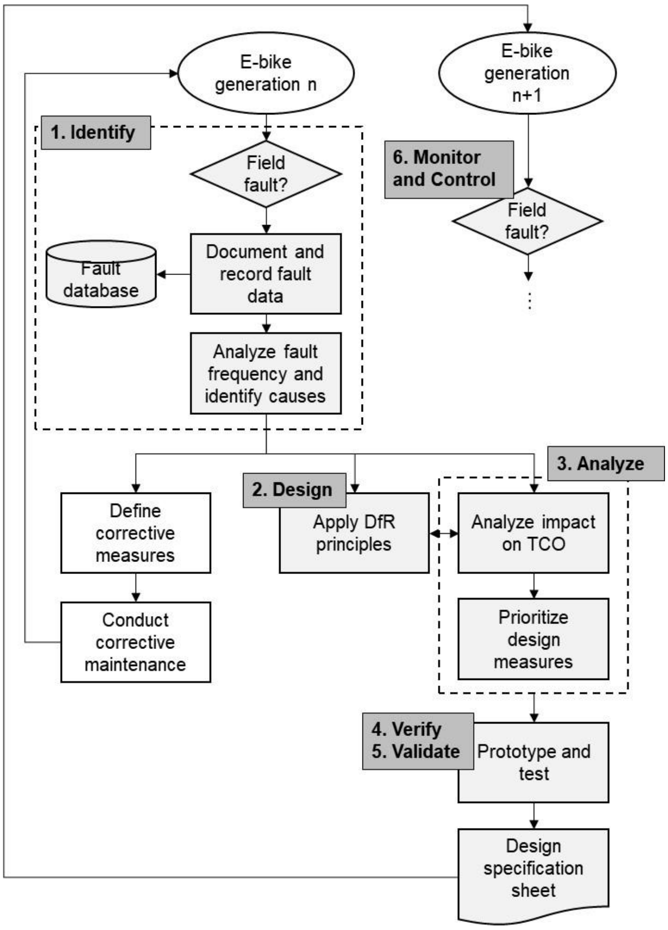


Fig. 3. Combined DfR – TCO design approach in the studied case

The resulting design measures and requirements were continuously documented in an evolving design requirements sheet to support the development of the subsequent product generation (Figure 3).

## 5. Discussion

The studied case from the electric micromobility sector provides new insights for theory and practice, as expected by this type of research [24,25].

In theoretical terms, the case study describes how DfR interplayed with TCO to guide solution evolution over product generations, resulting in the systematization of the novel combined DfR – TCO design approach. Although it is expected that measures resulting from Design for Reliability will directly impact the product costs, only a few previous studies considered this relation to the Total Cost of Ownership [e.g. 7]. Thus, this study contributes to the literature on the intersection between Design for Reliability and Total Cost of Ownership.

The present paper also provides insights into micromobility design issues. The growing literature on micromobility focuses mainly on the transportation perspective and user adoption patterns [1,18,20–22]. The electric micromobility sector faces novel challenges from electric mobility (e.g. battery application) and has developed following emerging business models (e.g. shared Product-Service Systems). Hence, the case study illustrates how electric micromobility is in an interesting position to be analyzed from the design research theoretical perspective. Finally, this study also contributes to the TCO research stream by discussing the TCO model from the perspective of a shared mobility services provider operating a fleet of e-bikes.

This research is intrinsically limited to a single case in one sector. In order to avoid bias and increase validity, the researchers considered empirical data from multiple sources. Gathered data were triangulated and related to the literature to derive the findings following an inductive approach. Nevertheless, single-case results have limited external validity, which will need to be addressed by future research in the field. Although the description provided in this paper is limited to a single case in one sector, it indicates a direction to be further explored in future works and similar settings. In practical terms, the systematized DfR – TCO design approach can serve as an inspiration for other companies, especially those operating in conditions in which both reliability and TCO have a critical role.

## 6. Conclusion

This paper presents a combined DfR – TCO design approach that emerged from the practice of a shared e-bike provider in the micromobility industry. The paper also presents a micromobility case description from the design research perspective. The case study illustrates that the emerging electric micromobility sector may provide interesting insights to be considered from the design research perspective.

The presented results open opportunities for further related studies. Researchers can continue following the studied case to provide a longitudinal perspective on product evolution by analyzing reliability and TCO quantitative estimates. Additional research opportunities include multiple case studies with other electric micromobility providers and extending the analysis beyond micromobility. Finally, prescriptive studies may assess the application of the proposed combined DfR – TCO design approach.

## Acknowledgments

The authors thank the company that made this study possible. The authors also thank Felix Kunert for his support in data analyses. Eduardo Zancul is supported by the São Paulo Research Foundation (FAPESP) under Grant Agreement No 2022/03437-0.

## References

[1] O'hern S, Estgfaeller N. A scientometric review of powered micromobility. Sustain. 2020; 12: 1-21. https://doi.org/10.3390/su12229505.
[2] Reck DJ, Martin H, Axhausen KW. Mode choice, substitution patterns and environmental impacts of shared and personal micro-mobility.

Transp. Res. Part D Transp. Environ. 2022; 102: 103134. https://doi.org/10.1016/j.trd.2021.103134.
[3] Chang AY, Miranda-Moreno L, Clewlow R, Sun L. Trend or Fad? Deciphering the Enablers of Micromobility in the U.S. SAE International; 2019. https://www.sae.org/binaries/content/assets/cm/content/topics/micromobility/sae-micromobility-trend-or-fad-report.pdf.
[4] Lazarus J, Pourquier JC, Feng F, Hammel H, Shaheen S. Micromobility evolution and expansion: Understanding how docked and dockless bikesharing models complement and compete – A case study of San Francisco. J. Transp. Geogr. 2020; 84: 102620. https://doi.org/10.1016/j.jtrangeo.2019.102620.
[5] Paganin L, Borsato M. A Critical Review of Design for Reliability - A Bibliometric Analysis and Identification of Research Opportunities. Procedia Manuf. 2017; 11: 1421-1428. https://doi.org/10.1016/j.promfg.2017.07.272.
[6] Ellram LM. Total cost of ownership; An analysis approach for purchasing. Int. J. Phys. Distrib. Logist. Manag. 1995; 25: 4-23. https://doi.org/10.1108/09600039510099928.
[7] Waghmode LY, Patil RB. Reliability analysis and life cycle cost optimization: a case study from Indian industry. Int. J. Qual. Reliab. Manag. 2016; 33: 414-429. https://doi.org/10.1108/IJQRM-11-2014-0184.
[8] Yang L, Niu R, Xie J, Qian B, Song B, Rong Q, Bernstein J. Design-for-reliability implementation in microelectronics packaging development. Microelectron. Int. 2011; 28: 29-40. https://doi.org/10.1108/13565361111097092.
[9] Silverman M, Kleyner A. What is design for reliability and what is not? Proc. - Annu. Reliab. Maintainab. Symp. 2012. https://doi.org/10.1109/RAMS.2012.6175520.
[10] Go TF, Wahab DA, Hishamuddin H. Multiple generation life-cycles for product sustainability: The way forward. J. Clean. Prod. 2015; 95: 16-29. https://doi.org/10.1016/j.jclepro.2015.02.065.
[11] Palmer K, Tate JE, Wadud Z, Nellthorp J. Total cost of ownership and market share for hybrid and electric vehicles in the UK, US and Japan. Appl. Energy. 2018; 209: 108–119. https://doi.org/10.1016/j.apenergy.2017.10.089.
[12] Patil M, Majumdar BB, Sahu PK. A Comparative Evaluation of the Total Cost of Ownership between Electric Two-Wheelers and Motorized Two-Wheelers from an Indian Perspective. Transp. Res. Rec. 2022; 5: 526-550. https://doi.org/10.1177/03611981221077087.
[13] Guo Y, Kelly JA, Clinch JP. Variability in total cost of vehicle ownership across vehicle and user profiles. Commun. Transp. Res. 2022; 2. https://doi.org/10.1016/j.commtr.2022.100071.
[14] Korzilius O, Borsboom O, Hofman T, Salazar M. Optimal Design of Electric Micromobility Vehicles. IEEE Conf. Intell. Transp. Syst. Proceedings, ITSC. 2021; 1677–1684. https://doi.org/10.1109/ITSC48978.2021.9564429.
[15] Kristensen HS, Remmen A. A framework for sustainable value propositions in product-service systems. J. Clean. Prod. 2019; 223: 25-35. https://doi.org/10.1016/j.jclepro.2019.03.074.
[16] Sousa-Zomer TT, Magalhães L, Zancul E, Cauchick-Miguel PA. Lifecycle Management of Product-service Systems: A Preliminary Investigation of a White Goods Manufacturer. Procedia CIRP. 2017; 64: 31-36. https://doi.org/10.1016/j.procir.2017.03.041.
[17] Raheja D. Design for Reliability Paradigms. Raheja DG, Gullo LJ, editors. Hoboken: John Wiley & Sons, 2012.
[18] F. Highway Administration. Micromobility: Emergence of New Transportation Modes, 2022. https://rosap.ntl.bts.gov/view/dot/54137/dot_54137_DS1.pdf?
[19] Taxonomy and Classification of Powered Micromobility Vehicles J3194_201911, 2019. https://www.sae.org/standards/content/j3194_201911/.
[20] Fishman E. Bikeshare: A Review of Recent Literature. Transp. Rev. 2016; 36: 92-113. https://doi.org/10.1080/01441647.2015.1033036.
[21] Christoforou Z, Gioldasis C, de Bortoli A, Seidowsky R. Who is using e-scooters and how? Evidence from Paris. Transp. Res. Part D Transp. Environ. 2021; 92: 102708. https://doi.org/10.1016/j.trd.2021.102708.
[22] Orozco-Fontalvo M, Llerena L, Cantillo V. Dockless electric scooters: A review of a growing micromobility mode. Int. J. Sustain. Transp. 2022; 1–17. https://doi.org/10.1080/15568318.2022.2044097.
[23] Severengiz S, Schelte N, Bracke S, Analysis of the environmental impact of e-scooter sharing services considering product reliability characteristics and durability. Procedia CIRP. 2020; 96: 181-188. https://doi.org/10.1016/j.procir.2021.01.072.
[24] Yin RK, Case study research: design and methods. Thousand Oaks: Sage, 2014.
[25] Eisenhardt KM. Building Theories from Case Study Research. Acad. Manag. Rev. 1989; 14: 532-550. https://doi.org/10.2307/258557.