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Towards Sustainable Urban Mobility: Integrating Design for Circular Economy-Principles in E-Scooter Development

Merlin Stölzle[a,*], Sophia Giunta[b], Chantal Rietdorf[b,c], Valentin Honold[b,c], Daniel Roth[a], Matthias Kreimeyer[a], Alexander Sauer[c]

[a]*Institute for Engineering Design and Industrial Design, Pfaffenwaldring 9, 70569 Stuttgart , Germany*
[b]*Fraunhofer Institute for Manufacturing Engineering and Automation, Nobelstr. 12, 70569 Stuttgart, Germany*

[c]*Institute for Energy Efficiency in Production, Nobelstr. 12, 70569 Stuttgart, Germany*

* Corresponding author. Tel.: +49 (0) 711 685 – 66058. *E-mail address:* Merlin.Stoelzle@IKTD.Uni-Stuttgart.de

Abstract

Innovative urban mobility solutions, especially e-scooters, are becoming increasingly popular. However, due to their often-short lifespan their environmental footprint needs improvement. Circular economy strategies regarding modules and components seem to be a possible way to improve the environmental impact. This research aims to improve aspects of the Life Cycle Assessment (LCA) with the help of Design for Circular Economy-principles (DfCE). For this purpose, a two-step House of Quality (HoQ) approach firstly translates requirements from a LCA into DfCE-principles. Secondly, the most influential components of a generic e-scooter are identified to derive recommendations regarding a low environmental impact circular scooter design.

Keywords: Life Cycle Assessment; Design for Circular Economy; House of Quality; E-Scooter

1. Introduction and motivation

As the need for mobility increases, the transportation sector continues to have a significant impact on the climate, environment and human health. In 2021, the mobility sector accounted for almost 19.5% of Germany's greenhouse gas emissions (including cargo transportation) [1]. Therefore, the need to develop strategic approaches that help to minimize these effects becomes crucial. In particular, there is a growing focus on reducing the intensity of emissions from private transport [2].

In urban centers, innovative mobility concepts are becoming increasingly relevant. The emphasis in this context is on creating low-threshold solutions for individual transportation [3], as challenges arise not only from increased environmental pollution but also from high traffic density and the rapid growth of the vehicle population. In this context, e-scooters are gaining importance as a promising alternative to cars for short trips in urban areas. According to Degele et al [4], e-scooters are mainly used for distances between 1 and 6 km. This range aligns closely with most car trips in urban areas, particularly in large cities and metropolitan regions. Replacing car journeys with e-scooters can result in a reduction in noise and environmental pollution, as well as traffic jams [4].

However, using e-scooters is also associated with various problems and challenges. These include issues related to the manufacturing of battery system, the limited mileage, and the short service lives of the vehicles of approximately two years for current models [5].

As a result, life cycle assessments (LCAs) of e-scooters often highlight their low utilization efficiency and the significant environmental impact associated with it [6]. To address these issues, adopting a circular economy approach focused on reusing as many components of the scooter as possible can

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extend the service life of e-scooters. Accordingly, a detailed focus must be placed on the end-of-use (EoU) phase of these vehicles, to examine to which extent extending the service life or recycling the entire product or individual components can reduce the environmental impact of the overall system. This consideration leads to the research question (RQ): "How can e-scooter components be redesigned using Design for Circularity criteria to better align with the requirements of LCAs?"

2. Research methodology

To answer the research question, three key areas are explored through focused literature research, each addressing a specific part:

1) What implicit requirements for e-scooters can be derived from LCAs?

2) What circular design principles (Design for Circular Economy – DfCE) are available to developers for designing products, thus influencing the fulfillment of the identified requirements?

3) What does the product structure of a generic e-scooter look like?

To link these aspects, an integrated approach combines the findings from the literature analyses. Using an adjusted Quality Function Deployment methodology, the findings on the requirements of LCAs, design features of circular products and components of the e-scooter are compared and examined for mutual influences.

2.1. Quality Function Deployment

Quality Function Deployment is a method mainly used by large industrial companies and research organizations to plan quality in the development or improvement of products, services and processes [7]. The central approach of QFD is the "House of Quality" (HoQ), which is used to translate customer wishes and requirements into technical specifications. Figure 1 shows the matrix in its basic structure.

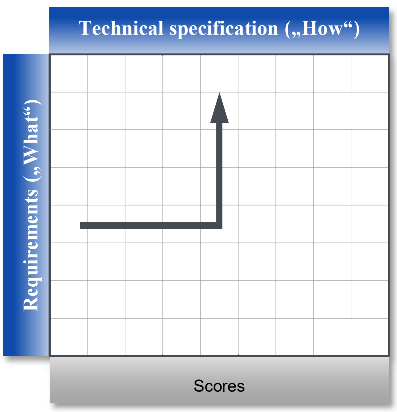

Fig. 1. Basic structure of an HoQ

To link the requirements from the LCAs, the DfCE criteria, and the components of an e-scooter, a two-step approach is used. Two HoQs are structured to identify the key components of e-scooters that can most effectively reduce their environmental impact, as identified through LCA. In the first House of Quality, the findings derived from the literature research on the LCAs of e-scooters are mapped against DfCE criteria and analyzed to understand their alignment. In the second House of Quality, these DfCE criteria are further evaluated in relation to a generic list of e-scooter components.

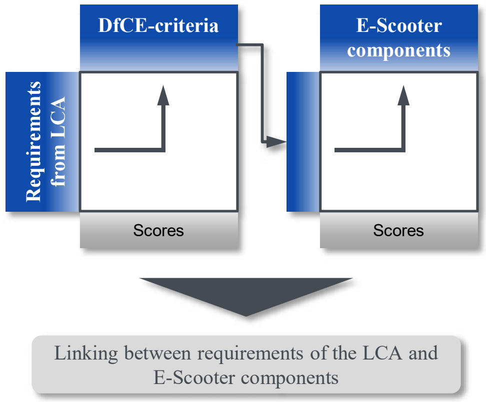

Fig. 2. Methodology of this study

This two-step approach aims to identify the DfCE criteria most crucial for improving the LCA results and to identify which parts of the e-scooters have the highest potential for integrating these design criteria.

Based on the results of both HoQs, practical design recommendations are then formulated to support the product development phase, ensuring better environmental performance of the e-scooter.

2.2. Identification of levers and requirements to improve the LCA result

In order to derive requirements for e-scooter design from an environmental perspective, a systematic literature review was carried out using the Prisma flow diagram [8]. The research aimed first to identify LCAs on e-scooters and subsequently identify the key factors influencing the LCA results of the respective studies. This allows to derive levers improving environmental performance [6]. The literature search was carried out in January 2024 using the Scopus database and the following search string:

TITLE-ABS-KEY (LCA OR "life cycle assessment" OR "life cycle analysis" AND "electric scooter*" OR "e scooter" OR "micro mobility")

All studies available in either English or German were considered, and no time restrictions were imposed. 33 data records were found during the search in the Scopus database. In the first step, the "screening" phase, the titles and abstracts of the studies were reviewed. Studies that carried out an LCA of battery-powered e-scooters were marked as relevant. During this process, twelve studies were excluded for further consideration. The remaining 20 studies identified as relevant were then assessed for eligibility by full-text analysis. In this step, five other studies were excluded because they did not perform an LCA of e-scooters, but of, for example, solar charging stations [9] or because access to the full study was possible. The process resulted in a final set of 15 studies that were considered for identifying of levers for improvement.

Table 1. Factors influencing the life cycle assessment results, categorized by life cycle phase.

Life cycle stage	Lever
Raw material production	Type of material for the frame and battery [6, 10–12]
Manufacturing	Energy sources for the manufacturing process [6]
Use phase	Service life of the e-scooter [6, 13–15]
	Intensity of use [16]
	Driving behavior and modal shift [17]
	Rebalancing strategy [18, 19]
	Logistics and maintenance [13, 19]
	Energy source for charging [10]
EoU phase	Material recycling [15]
	Reuse of components and/or e-scooters [13]

The outcomes of the analyzed studies have been put in the first HoQ and analyzed in relation to selected DfCE criteria.

2.3. Identification of circular design principles

Due to the characteristics of circular products that have already been extensively researched in the literature (mostly in the context of "DfX" approaches), these were used as the basis for the definition of circularity. Accordingly, circularity describes the sum and degree of fulfillment of relevant circular product characteristics.

However, there was no holistic summary of different DfX approaches across different circular economy application areas and authors. A systematic literature search was carried out to comprehensively collect product characteristics relevant to the circular economy. The aim of the research was to find existing collections of characteristics. The derivation of DfCE principles based on the literature did not fit the scope of the study. The search was conducted within the research databases Scopus and Web of Science. The search term used consisted of synonyms for "guideline" as well as terms associated with the circular economy:

TITLE-ABS-KEY ("design for" OR "design guideline") AND ("circularity" OR "circular economy" OR disassembl* OR reassembl* OR remanufatur* OR repurpos* OR reus* OR repair OR refurbish* OR recycl* OR "end-of-life" OR "end of life").

By restricting the search to articles published within the last 6 years, around 3000 papers were identified and checked for relevance. A three-stage exclusion process was used. The title and keywords were checked in the first stage, the abstract in the second and the entire content in the third.

This process led to the identification of approximately 200 independent DfCE features, which were then logically grouped and summarized for reduction to a practicable amount.

From these, 50 characteristics were extracted for application in the House of Quality. These characteristics can be divided into the following general categories:

Table 2. Overview over extracted Design for Circular Economy principles.

Category (Design for …)	Examples
Efficient use	Low weight, low size/volume, …
Replaceability	Wear parts, visible parts, …
Identification	Material composition, recycling instructions, …
Separability	Components, incompatible materials, toxic substances, …
Standardization	Modules, fastener types, assembly tools …
Durability	Wear, dirt resistance, corrosion resistance, …
Avoidance	Toxic substances, need for calibration, …
Reduction	Parts, fasteners, joints, …
Reprocessability	Cleanability, restorability, …
Assessability	Condition, usage data, …

2.4. Identification the components of a generic e-scooter

To generate a generic e-scooter Bill of materials (BoM), 13 scooters were examined for their component structure. Table 3 shows the vehicles examined:

Table 3. Examined e-scooters.

Brand	Models
Egret	EY!1, EY!2, EY!3, EY!6, One; Pro, X
Streetbooster	One, Two; Castor, Pollux, Sirius, Vega

As the vehicles were not available for disassembly, components were examined using supporting materials. Depending on the brand and model, these supporting materials included manuals, disassembly videos from third parties or simple images that provided information on the installed components.

To determine the potential for optimizing components in terms of circularity, the components were not broken down to the individual screw level. Instead, functional assemblies were identified which shared common properties in terms of material, size and interconnectivity and whose disassembly and joint optimization were considered useful.

The following components were identified:

Table 4. Extracted e-scooter BoM.

Components	Parts
Handlebar	Headlights, accelerator, control panel, grip
Stem	Steering tube, folding mechanism, bearings

Front fork	Spring, damper, trailing arm
Front wheel	Rubber, rim
Chassis	Main frame
Battery	Cells, battery management system (BMS), interconnections
Power electronics	Converter, electric motor
Rear suspension	Spring, damper, trailing arm
Rear wheel	Rubber, rim

2.5. Consolidated House of Quality

The requirements identified in the LCAs, the design criteria, and the components of the generic e-scooter were integrated into the HoQs. Through several workshops with members of the authorship, the relationships within the HoQs were discussed and debated. This led to the development of a consolidated and refined HoQ.

3. Results

3.1. HoQ 1 – LCA Requirements and DfCE criteria

Completing the first HoQ revealed which LCA requirements could be addressed through DfCE criteria.

Most criteria target recyclability, ensuring a long service life and simplifying and improving the production process. To a lesser extent, the criteria promote high utilization, improve transportability and support the selection of durable and low-impact materials. All other LCA requirements are only partially and sporadically supported by DfCE criteria.

3.2. HoQ 2 – DfCE criteria and e-scooter components

According to the analysis of the second HoQ in the Two-Step HoQ approach, the component with the greatest environmental impact is the e-scooter batterypack. Many measures can lead to an improvement in the LCA here:

- The convenient assessment of the product condition is paramount, especially for the battery. To enable reuse and thus improve the environmental impact, it must be possible to evaluate whether a battery is suitable for reuse in the e-scooter or for other purposes. A representation of the cell condition is essential for this.
- When developing the battery, it is essential to know and consider all existing regulations due to the large number of legal requirements, but also to anticipate future regulations, in order to keep the components in circulation for as long as possible.
- Labeling the materials within the battery is particularly important for subsequent recycling and recovery of the materials, given that not all batteries consist of the same cell chemistry.
- As the battery must always be returned separately from the other components of the e-scooter, using quick-release but also tool-free connecting elements is recommended. This also makes it easier to replace the battery in the event of a defect and allows the rest of the e-scooter to be reused. However, attention must also be paid to the separability of components/materials within the battery.
- Physical protection of the battery must be ensured so that it can continue to be used for as long as possible.

Due to its high mass proportion and the central function, the e-scooter frame is the second most important part in terms of influence on the LCA results. Almost all DfCE features can be considered in its design, so a great deal of attention should be paid to their implementation during development. However, the choice of materials, especially the use of recycled materials, is considered particularly relevant for the development of the frame.

There is also potential to be exploited in the development of power electronics:

- Above all, the energy consumption of the e-scooter can be reduced through the power electronics and the motor.
- Here, too, condition assessment plays an important role. [...]
- Protecting the high-quality motor against external influences and damage is very important to ensure reusability, similar to the battery.
- Furthermore, design features that allow simple and quick disassembly for repairs and dismantling for later recycling are necessary.

The remaining e-scooter components were less relevant for the implementation of DfCE in favor of LCA results. However, it was possible to extract key design features that could be implemented within the e-scooter components:

- No incompatible materials within assemblies
- Ensuring the separability of components and different materials
- Use of recyclates in the product design
- Ensuring easy inspection
- Reducing the number of parts and connecting components, leading to fewer disassembly operations
- Labeling of components (digital product passport)
- Robust and durable product design
- Modularization of the product but also the use of modules across the product portfolio
- Easy cleaning of components

4. Conclusion

This study aimed at investigating how e-scooter components can be redesigned using circular design criteria to better meet the requirements of Life Cycle Assessments. To achieve this, two literature reviews were conducted: the first to identify factors influencing LCA results for e-scooters and the second to define design for circularity criteria. These criteria were then mapped using an adapted two-stage House of Quality to identify the most critical design criteria for improving the LCA results and to determine which e-scooter components have the highest potential for integrating these design criteria. Based on the results of both HoQs, practical design recommendations were specifically developed for the battery and e-scooter frame, as well as nine more general recommendations. These include using compatible materials, ensuring separability of components, incorporating recyclates, facilitating ease of inspection, reducing the number of parts and fasteners, component labelling (e.g., digital product passports), robust and durable designs, modularization, and facilitating component cleaning.

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