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Sustainable design of products: Balancing quality, life cycle impact, and social responsibility

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ABSTRACT

The shift towards sustainable mobility has increased the demand for energy-efficient and environmentally friendly vehicles, such as Hybrid Electric Vehicles (HEVs). However, designing HEVs that simultaneously meet high product quality, minimize environmental impact, and adhere to social responsibility standards remains a complex challenge. This study presents a decision-making model aimed at integrating these key sustainability criteria into the design and improvement of HEVs. The model combines three indices: the Aggregated Quality Index (AQI), Environmental Impact Index (EII) based on Life Cycle Assessment (LCA), and Social Responsibility Index (SRI), to assess and compare different HEV prototypes. By processing customer expectations, environmental impacts, and social responsibility considerations, the model predicts the optimal prototype that balances quality, environmental sustainability, and social standards. The findings demonstrate that applying this model can significantly enhance decision-making in sustainable vehicle development and support the creation of HEVs that better align with global sustainability goals. This approach has practical implications for automotive manufacturers aiming to innovate responsibly in the green mobility sector.

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1. Introduction

The diversity of considerations in product design reflects efforts towards achieving sustainable development. Actions in this area should simultaneously address quality, environmental impact, and social responsibility [1, 2]. This approach aligns with modern solutions that prioritize designing products satisfying customer needs, social acceptance, and environmental friendliness throughout their life cycle [3]. Integrating these considerations during product design sets milestones but also presents challenges due to the multitude and diversity of necessary decision-making criteria [4]. This process requires involving various decision-makers to establish comprehensive priorities across different application areas [5, 6].

However, research on sustainable product development often lacks equivalent and comprehensive analysis of these considerations, typically focusing on one or two aspects [1], as noted by authors in [7]. For instance, Life Cycle Assessment (LCA) methods continue to neglect product design and development (PDD) [8]. Considering all aspects collectively is challenging due to the interdisciplinary nature and scarcity of studies that address all sustainable development criteria – economic growth, social well-being, and environmental protection – simultaneously [9, 10].

Despite the development of several methods and tools supporting sustainable product design, there is still a lack of unified consensus, including clear frameworks, methods, and standards for supporting prospective design for sustainable product development that integrates quality, environmental, and social responsibility aspects. Critically discussed conceptual design processes providing analysis of current products and alternative product solutions (prototypes) in a multidimensional evaluation process considering sustainable development criteria (quality, environmental, and social responsibility) are notably absent, and therefore were identified as our research gap.

The main research question of this research is: "How to support the process of improving current products based on possible design prototypes in a multidimensional approach that integrates product quality (customer satisfaction), environmental impact of the product life cycle, and social responsibility compliance?" We assumed that it can be answered by developing a model that provides three separate indexes: i) quality, ii) environment, and iii) social responsibility, subsequently aggregated into a coherent decision-making indicator, used to rank the product design and improvement for their compatibility with sustainable development criteria.

This research aims to develop a decision-making model to anticipate the direction of improving current products based on prototypes (production alternatives) methodically verified in a multidimensional approach encompassing key aspects of sustainable development: quality, life cycle environmental impact, and social responsibility compliance.

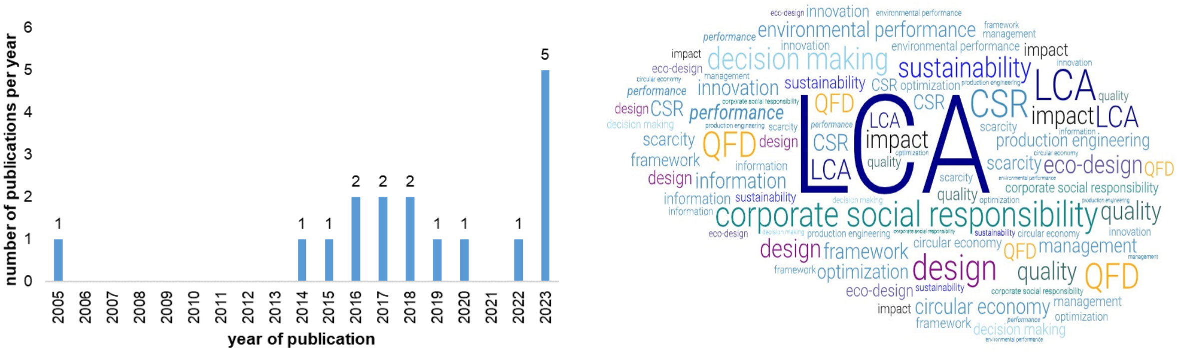
The model is primarily dedicated to managerial decision-making in product design and production management, aiming to support private individuals, companies, and public entities in sustainable product development decisions, focusing on achieving socially responsible production engineering that also ensures high-quality offered products and environmental friendliness.

2. Literature review

A literature review was conducted on product design and improvement concerning sustainable development aspects: quality, environmental impact throughout the life cycle, and social responsibility. Due to the limited popularity of simultaneously combining these aspects, the review was conducted in three stages, analysing works that address: i) customer satisfaction with product quality while reducing negative environmental impact throughout the entire life cycle; ii) customer satisfaction with product quality considering social responsibility; iii) product LCA considering social responsibility.

All analysed works came from the Web of Science (WoS) international database. The literature review was conducted in March 2024 within a specified timeframe. Works were categorized based on title, abstract, and keywords. The identified works included: i) LCA, product design, and customer (10 out of 28 works); ii) socially responsible design, product (7 out of 82 works); iii) LCA, product design, quality, and social responsibility (0 works). Initially, a preliminary selection was based on publication abstracts, resulting in a lower number of works analysed compared to those identified.

In total, 17 relevant works were identified, including 12 scientific articles and 5 conference papers. The selected works were further analysed for their distribution, as depicted in Fig. 1. Next, the keywords included in the selected papers were analysed using the WordArt software "Word Cloud" tool. The word cloud visually presents the frequency of individual keywords, with larger font sizes indicating higher frequency of occurrence (Fig. 1).



(a) (b)

Fig. 1 Analysis of: (a) publication trends and future developments in the research area of QESR decision-making for sustainable product design and improvement; (b) word cloud for Web of Science database metasearch keywords

The first publication dates from year 2005, but no publications were revealed be-tween 2006 and 2013. Search keywords emerged from 2014 onwards, with only up to two publications per year until 2023, where a slightly higher number (5 publications) was noted. These findings suggest that the selected research area is in a developmental phase, characterized by numerous research gaps, making it an area worthy of further investigation.

Keyword analysis revealed that across the 17 reviewed studies, there were a total of 162 unique keywords (including those provided by authors and indexed in WoS). The most frequently occurring keyword (12 times) was "LCA" (including variations like “life cycle assessment”). Following closely were: "corporate social responsibility" (6), "design" (6), "QFD" (6), "decision making" (5), and "sustainability" (4). Keywords related to "eco-design" (3), "impact" (3), and "quality" (3) appeared slightly less frequently. The remaining keywords appeared twice (11 words) or once (92 words). The high-frequency keywords related to the analysed thematic area and resulted from the search scope used in the selection of works in WoS.

Subsequently, mutual citation analysis was conducted to identify the most frequently cited studies critical to the development of the analysed research area. This analysis was supported by the Gephi 0.10.1 software. Initially, a network of connections was established among the 17 reviewed publications. Subsequently, the focus was narrowed down to the primary citations occurring among these works (Fig. 2).

Fig. 2 Mutual connections among the key publications in content analysis in the Gephi 0.10.1 software, based on the metasearch of the Web of Science database

The 17 analysed studies collectively contained 585 citations (bibliographic entries). When examining their mutual citations, inconsistency was observed both among the studies and within the cited works. This inconsistency may stem from the limited number of studies addressing the chosen thematic area, as well as the previously identified low level of development in this research domain. Among all references, only four most frequently cited works were identified, namely [11-14]. These studies encompassed LCA, decision support, and customer expectation processing using the Quality Function Deployment (QFD) method, acknowledging these issues as integral to sustainable product design.

All selected works underwent synthetic content analysis. It was observed that the most frequently proposed solutions for assessing product quality and environmental impact in the life cycle involved combining QFD for processing customer expectations and LCA for environmental impact assessment [15-18]. Besides combining results from QFD and LCA methods, other approaches were also employed, such as: integrating Failure Mode and Effects Analysis (FMEA), Theory of Inventive Problem Solving (TRIZ), and Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (FTOPSIS) to develop product criteria rankings indicating the most favourable prototypes for existing products [14]; conducting surveys to gather customer expectations regarding product quality and subsequently processing them considering LCA results for different product materials [19]; developing decision support processes during the design phase by modelling LCA outcomes based on customer demand for alternative design solutions [9]; analysing customer sensitivity towards recyclable products [20].

Initial attempts at comprehensive integration of product quality assessment during development phase with environmental impact assessment of product solutions were presented, for example, in [21, 22].

Existing studies on socially responsible design focus on ensuring environmentally friendly products by analysing:

- Customer reactions to eco-labels in the context of their awareness and perceptions of corporate social responsibility [23];
- Social effects following technological support in the product life cycle, demonstrating that sustainable social development impacts sustainable environmental and economic development [24];
- Business social responsibility in the light of customer demand factors determining the expected level of eco-friendliness of new products [25];
- Changing roles and responsibilities of designers in environmentally conscious product design [26];
- Opportunities for implementing the Cradle to Cradle (C2C) approach in conceptual product design focusing on environmental and social benefits [27];
- Motivations of designers in making socially responsible decisions, indicating that the interaction of designer beliefs depends on business feasibility levels, and proper management should focus not only on social but also environmental aspects in product development [28];
- Characteristic product criteria and customer perceptions to align them with CSR [29].

Table 1 summarizes the results of the literature analysis. Following conclusions were drawn from the literature review:

- A limited number of studies (17) focus on product design considering quality (customer satisfaction), environmental impact in LCA, and social responsibility;
- The selected research area is not widely studied and is still in a developmental phase since 2005, with slow predicted growth in subsequent years, indicating significant research gaps;
- The most frequently discussed topics among the analysed works were LCA, corporate social responsibility, product design, QFD, and decision-making;
- Common proposed solutions for assessing product quality and environmental im-pact in the life cycle typically involve combining QFD for processing customer expectations and LCA for environmental impact assessment;

- Existing studies on socially responsible design aim to ensure environmentally friendly products, often overlooking the aspect of achieving customer-desired product quality.

Critically discussed conceptual design processes providing analysis of current products and alternative product solutions (prototypes) in a multidimensional evaluation process considering sustainable development criteria (quality, environmental, and social responsibility) are notably absent, and therefore were identified as our research gap.

Table 1 Summary of literature analysis results

Research Area	Description	Methods	Examples of studies
Product quality assessment and environmental life cycle assessment (LCA)	Acquiring and processing customer requirements for product quality and environmental impact assessment in product life cycle	QFD and LCA	[15, 16, 18, 30]
		Customer survey and LCA	[19]
		Customer demand data, LCA	[9]
		Analysis of customer sensitivity to recyclable products in their life cycle	[20]
	Acquiring and processing customer requirements for product quality and environmental impact assessment in product life cycle; analysis of product nonconformities and identification of product innovations	QFD, LCA, FMEA, TRIZ, FTOPSIS	[31]
	Combining product quality assessment with environmental impact assessment in product design	Customer surveys, TOPIS, LCA	[21 22]
Ensuring socially responsible design and environmentally friendly products	Customer reactions to product eco-labels in the context of their awareness and motives for perceiving corporate social responsibility	CSR, customer expectations for product eco-labels	[23]
	Assessment of social impacts in the case of technological support in the product life cycle	LCA, sustainable development criteria, CSR	[24]
	Modelling customer demand for the level of environmental friendliness of new products	Game theory, ethical operations, CSR	[25]
	Identification of customer expectations for product criteria for their compatibility with the CSR	CSR, analysis of customer expectations	[29]
	Analysis of changes in product roles and responsibilities in the field of conscious ecological product design	Focus groups with product designers	[26]
	Examining designers' motivations in socially responsible product design decisions	Socially responsible design (SRD), CSR	[28]
	Assessment of implementation potential of the C2C approach in conceptual product design for environmental and social benefits	C2C, analysis of qualitative and quantitative experiments	[27]

3. Model design

The research framework, including the developed model, is illustrated in Fig. 3. It involves determining the development direction of the current product by considering design alternatives (prototypes) in the context of sustainable development. The model primarily operates during the conceptual phase, translating and transforming the functional requirements of the product, its environmental impacts, and social acceptability into design parameters.

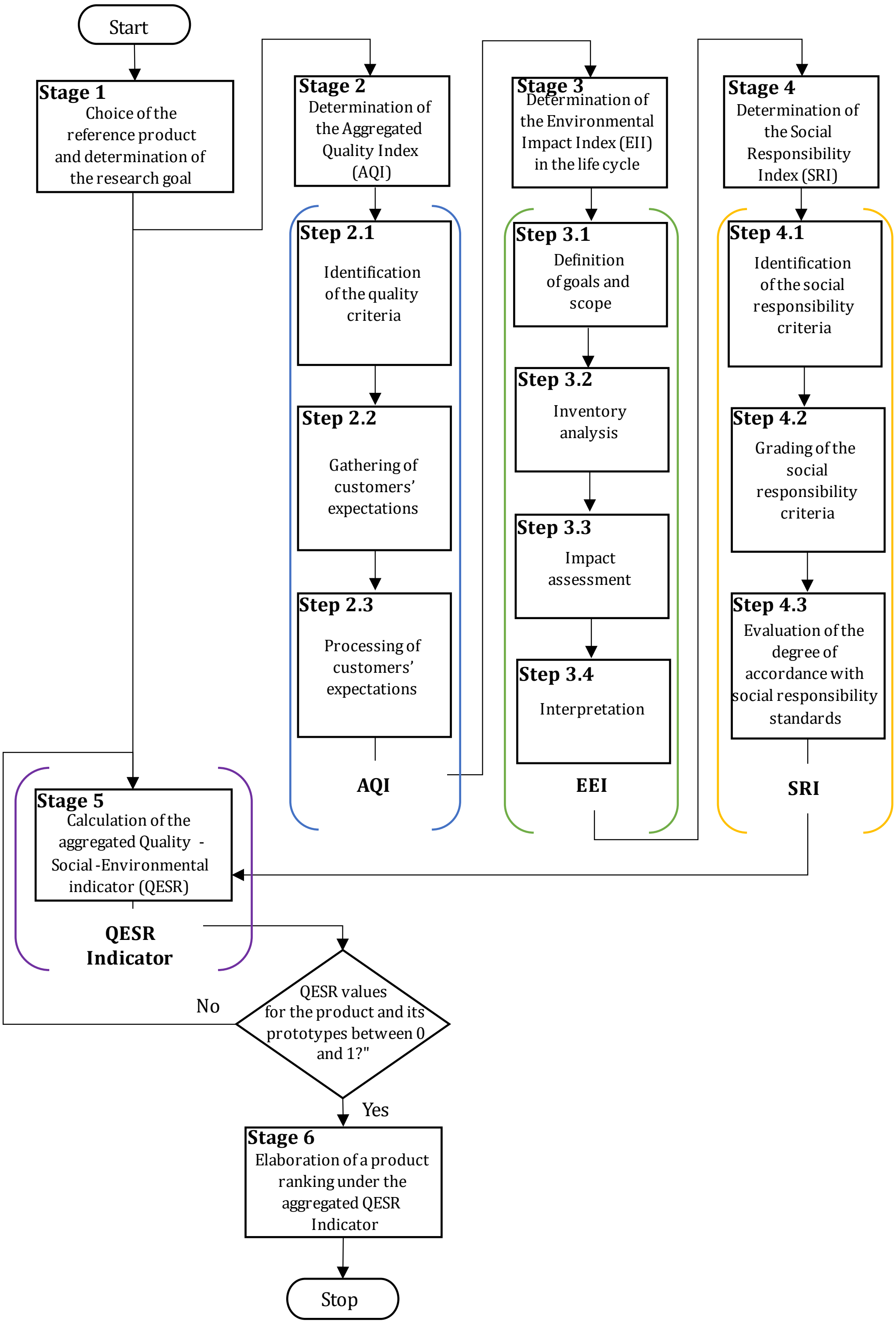


Fig. 3 Research design: model development for products enhancement with use of design prototypes within the context of sustainable development

The design parameters are both quantitative and qualitative, encompassing multidimensional aspects of the product and its prototypes in terms of meeting customer quality expectations, environmental impact throughout their life cycle, and fulfilling social responsibility criteria. This process involves a comprehensive and detailed analysis and prioritization of various sustainable development parameters. It integrates customer expectations and insights from interdisciplinary expert teams. Within the developed model, each key aspect (quality, environment, and society) can be considered independently or simultaneously using designated decision-making indicators. This ensures the model's versatility and flexibility in adapting to changing market demands. Based on the aggregated decision-making indicator, the model predicts the most favourable development direction for the product, aiming to simultaneously enhance customer satisfaction with product quality, reduce the product's negative environmental impacts throughout its entire life cycle, and achieve acceptable levels of social responsibility fulfilment.

Consecutive stages of model’s application are presented below.

3.1 Stage 1: Choice of the reference product and determination of the research goal

The selection of the product falls within the purview of the entity utilizing the model. This choice can be justified based on numerous factors, including the product's development stage (favouring the maturity phase), customer expectations, or the entity's individual preferences. The chosen product should be widely recognized and used, thereby increasing the efficiency of its analysis in subsequent stages of the model. This product serves as a reference product, representing a generalization of products of a particular type [32].

In accordance with the selected product, the entity defines the research objective using the SMARTER method (Specific, Measurable, Achievable, Relevant, Time-bound, Evaluate, and R - Reevaluate or Risks) [33]. It is assumed that the objective will involve determining the most favourable direction for enhancing the product using proposed alternative production solutions (prototypes), while simultaneously considering their: i) quality, ii) environmental impact throughout the life cycle, and iii) fulfilment of social responsibility criteria.

3.2 Stage 2: Determination of the Aggregated Quality Index (AQI)

The Aggregated Quality Index (*AQI*) is estimated for the current product and its prototypes. This index can be considered an aggregated measure due to its analysis of compliance and non-compliance (coverage) for all analysed quality criteria. It is considered based on two approaches: i) user-centred, where quality is the degree to which the product meets or exceeds customer requirements, and ii) production-driven, where quality is conformity to standards and design specifications [34, 35]. Following the works of [35-37], it is assumed that the assessment of product quality (and its alternatives) should be conducted using a multidimensional measure of product quality. This multidimensionality refers to the inclusion of various numbers and types of component dimensions (criteria or quality indicators) related to the product, such as performance, durability, or functionality [38]. Insights from an extensive literature review presented in [39] indicate that previous studies have focused on one-dimensional measures of product quality or provided quality assessments based on selected quality metrics. Therefore, aiming to fill this gap, original methodological frameworks for multidimensional assessment of product quality (and its alternatives/prototypes) have been developed.

The proposed method includes assessing the importance of product criteria (as determined by customers) and assessing the fulfilment of customer expectations regarding the quality of these criteria (while simultaneously considering customer expectations and expert team requirements). The product and its prototypes quality index are determined sequentially, as outlined in steps 2.1-2.3.

- Step 2.1. Identification of the quality criteria

Quality criteria relate to customer satisfaction with product usage. These criteria can be perceived as external (e.g., brand, price, country of origin) or internal [39]. In the proposed approach, product quality criteria refer to an internal conceptualization of quality perception [40]. This implies that modifying product criteria changes the nature of the product, thus affecting the perception of quality both objectively and subjectively. As stated in [41], objective quality determines whether a product fulfils its functions as expected by customers. Objective quality also encompasses engineering design, where product criteria are measured to shape perceived quality as objectively recognized by experts. On the other hand, subjective quality concerns customers' perception of product quality and serves to conceptualize it [39, 42].

Product quality criteria can be selected according to the ISO/IEC 25010 standard, which includes criteria such as functional suitability, performance, compatibility, usability, reliability, security, maintainability, and portability [43]. Additionally, the selection of criteria can be based on foundational research in this area, such as [34, 37] and aligned with other works from a literature review [35, 39, 44]. Based on these sources, the proposed model focuses on internal quality criteria. Criteria should be chosen that relate to the target product (the subject of the study). However, reducing the analysis to criteria that meet all quality indicators is impractical and inefficient for assessing overall product quality. As mentioned in [45], identifying numerous product criteria, most of which are insignificant in the holistic perception of product quality, is unnecessary. Therefore, following [45], it is advisable to limit the criteria to key factors that have the greatest impact on customer satisfaction with product usage [46].

The selection of criteria is carried out by an expert team, chosen based on their knowledge and qualifications relevant to the study and analysis. Methodical selection of expert teams is outlined in [47, 48]. According to literature reviews, a sufficient number of experts can range from six to eight [49], four to fifteen [50], or, as proposed in [51], an optimal team size could be ten experts. Following [52], experts may include employees of companies manufacturing the selected product, assuming that this product is interpreted as a reference product (products of varied brands differing in specifics but serving the same purpose and belonging to the same type). Delegating decision-making to an expert team, including employees of manufacturing companies, reflects current practices of well-functioning organizations where employees participate in participatory practices and teamwork, and interdisciplinary or multifunctional teams are key assets in the improvement process [53].

This expert team can effectively select criteria, basing their choices on the specificity, usefulness, and often ambiguity of the criteria. The selection of criteria is carried out according to the product catalogue (specification), which includes key product criteria in terms of customer usage. To efficiently select the main criteria, it is recommended to utilize teamwork and decision-making methods [52], such as Preliminary Criteria Reduction (PCR) [54]. The total number of quality criteria should be below 10, adhering to the principle of a minimum number of 7±2 [46].

Since quality criteria have different parameters (measures, specifications), it is necessary to characterize them for further evaluation. This characterization involves defining the parameters of the criteria, such as those used to measure their quality, e.g., parameters in the product catalogue (specification). The magnitude of these parameter measures should be expressed in international metric units, such as value, value range, or a verbal description of the criterion's state. It is assumed that the current (marketed) product is characterized according to its specification, meaning that the criteria are expressed in their current state, as in the product catalogue.

The model concept assumes that the direction of product improvement will be determined based on a multidimensional assessment of various modifications of this product, referred to as design solution alternatives (product prototypes). These prototypes are developed as modifications of the current product's quality criteria. The number of prototypes should adhere to the principles of effective comparison, so the total number of prototypes along with the reference product should not exceed 15 [55], where the minimum number should meet the 7±2 principle [46]. Prototypes are developed as modifications of the current state of the reference product's criteria. Modifying current criteria to hypothetical ones is done according to the Pareto principle [21 ,56, 57], meaning that various modifications of quality criteria, changing their characteristic values (parameters), are proposed by increasing or decreasing them by 20 % in a sequential manner. Decisions regarding these modifications are made by the previously selected expert team.

- Step 2.2. Gathering of customers' expectations

To assess the quality of the product and its prototypes, obtaining customer expectations is essential. Customers express their expectations regarding the importance (weights) of product criteria and their satisfaction with the quality fulfilment of these criteria. At this stage, the expert team plays a crucial role in supporting the assessment process of quality criteria fulfilment. Incorporating the Voice of Customer (VoC) [58] and expert opinion is important because customers tend to express their satisfaction through overall ratings or perceptions of product quality, rather than objective measures of criteria compliance with technical standards [35, 59]. Meanwhile, the expert team can verify these assessments by analysing their alignment with customer requirements, for example, through focus groups [51].

Customer expectations are gathered through exploratory research, with survey research being the most popular method used in customer satisfaction studies [60]. If the survey responses are imprecise, in-depth interviews may be necessary. The recruitment strategy for survey participants should be well-planned to ensure high-quality results and sample representativeness. It is expected that the database will be built on real customer experiences with the product, with customers participating in the survey having used the studied product for at least a month [61]. The representative sample size of customers can be estimated using the method from [57].

During the survey, customers rate the importance (weights) of the product's quality criteria, including its prototypes. The importance rating reflects the significance of these criteria in terms of their utility in the product. The ratings are given on a 5-point Likert scale [62], where 1 represents a criterion that is insignificant, and 5 represents a criterion that is significantly important.

Additionally, customer satisfaction with the fulfilment of these criteria is assessed during the survey. This assessment indicates the extent to which each criterion meets customer expectations regarding the product's utility. Satisfaction ratings are also provided on a Likert scale [62], where 1 represents a criterion that does not meet the expected quality, and 5 represents a criterion that significantly meets the expected quality.

An advantage of the proposed model is its ability to compare the *i-th* product criterion against the *j-th* product alternative, ensuring increased precision in the assigned ratings. This approach involves a pairwise comparison of the same criteria across different solution variants, which is effective in multi-criteria decision-making [12].

- Step 2.3. Processing customers' expectations

After obtaining customer expectations regarding the importance of criteria, the next step is to rank the criteria's importance to form them into groups distinguished by the significance of these criteria to customers. Due to the assumption regarding the total number of quality criteria (7±2) [46] and the adopted five-point scale for rating the im-portance of these criteria, the criteria weights are calculated as the arithmetic mean of the criteria importance ratings [55, 57].

Subsequently, the assessment of product and its prototypes quality is conducted. To maintain the multidimensionality of this assessment corresponding to a varying number of criteria across different component dimensions (criteria or quality indicators) of the product [38], an expert assessment of quality is proposed, which applies to calculating the level of multi-aspect quality for any products or processes that may be in the design, production, or operational phase. For this purpose, Eq. 1 is utilized to calculate the *AQI*:

$$AQI_i = \frac{\sum w_{ij} q_{ij}}{\sum w_{ij}} \tag{1}$$

where: i – product or prototype; j – criterion, $j, i = 1, 2, \ldots, n$; w_{ij} – weight of the *j-th* criterion for the *i-th* product or prototype; q_{ij} – quality of the *j-th* criterion for the *i-th* product or prototype.

AQI pertains to customer satisfaction with the utility of the product (and its pro-posed alternatives). It enables the development of a product ranking based on customer satisfaction with their quality. The maximum value of the *AQI* corresponds to the most favourable product.

3.3 Stage 3: Determination of the Environmental Impact Index (EII) in the life cycle

The model assumption is, that the direction of product improvement will be considered regarding the environmental impact of its prototypes throughout their life cycle. To achieve this, an Environmental Impact *Index (EEI)* for the product (and its prototypes) over the entire life cycle has been developed. This indicator is determined using results obtained from the LCA method. It is a structured, comprehensive, and internationally standardized method that quantitatively assesses important emissions and resources, including environmental and societal impacts, resource depletion, and other issues arising throughout the life cycle of any product (as well as processes or services). LCA is recognized as an effective decision-support method that, when supplemented with other tools, contributes effectively to more environmentally sustainable consumption and production practices.

LCA is often applied in the area of product design (including improvement) as a specialized method dedicated to strategic assessments of new concepts [63]. It is most often conducted in accordance with ISO 14040 [64], which includes phases such as defining goals and scope, inventory analysis, impact assessment, and interpretation [61] (Fig. 4).

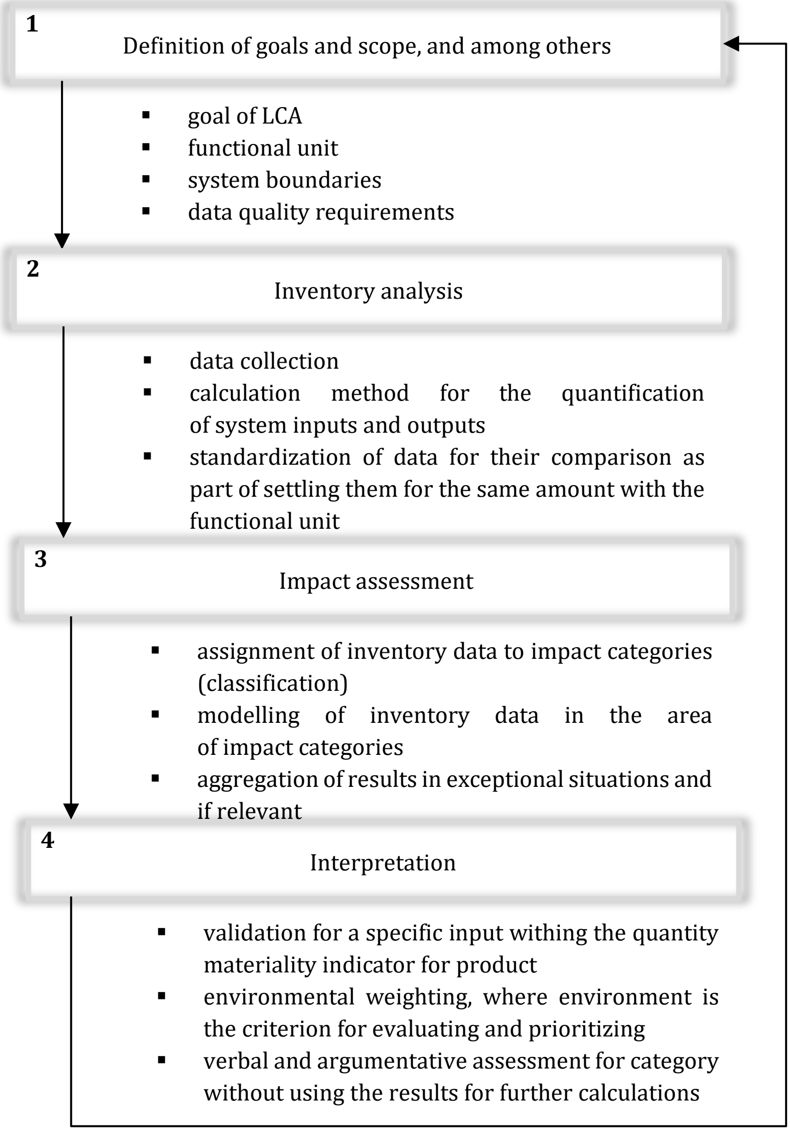


Fig. 4 LCA in ISO 14040 norm [63]

In our model, the existing product is compared with existing products (prototypes, modified products within the framework of the current/real product). The challenge of using LCA in this approach is conditioned by the lack of complete definitions and data for estimation during the design process, where the concept and architecture of prototypes are developed. Consequently, the use of LCA is focused on answering environmental protection questions, such as "Which of the proposed design solutions is more environ-mentally favourable?" The ability to answer this question accurately lies with specific experts, ideally environmental experts [63].

The full and detailed scope of an LCA system begins with the extraction and pro-cessing of materials, continues through production, usage, and ends with the product's end-of-life stage, adhering to the fundamental cradle-to-grave approach for life cycle assessment [65]. LCA involves analysing each stage of material transformation, including intermediate states, culminating in the synthesis of the final product [66, 67]. LCA application can be supported by software, e.g.: OpenLCA, SimaPro, Gabi [68, 69].

For less rigorous LCA applications, it is preferable to use Level 1 LCA or Level 2 LCA [70]. These levels were deemed adequate for the proposed model. LCA should be conducted for the reference product (current and commercially available), resulting in a single $EII > 0$ value, such as for carbon footprint, which has a measurable, numerical nature.

After evaluating the reference product, a prospective life cycle assessment (LCA) of its prototypes – alternative products modified according to quality criteria parameters and specifications – is conducted. LCAs for prototypes still in the design phase face inherent limitations due to incomplete data, which can result in compilation challenges and an increased risk of errors [63]. Traditionally, scenario analysis has been employed to conduct LCAs for products during the design phase [71, 72].

Our research, however, seeks to advance this process by more comprehensively integrating results from various model stages, addressing qualitative, environmental, and social aspects. To this end, we propose a novel approach that predicts environmental impact changes in prototypes relative to the quality levels of the reference product. This method utilizes simplified modelling of LCA value changes, aligning with quality parameter modifications, and adheres to the Pareto principle [73]. For instance, if the current quality level of a product results in a particular LCA outcome, a 20 % increase in quality level is expected to produce a corresponding 20 % increase in the LCA result, as previously tested in [21, 56].

The prospective and simplified LCA for product prototypes is conducted following Eq. 2 [21]:

$$EII_i = EII\ (1 + p) \tag{2}$$

where: EII – reference product in its life cycle, p – percentage change of EII represented in decimal form; i – prototype, i = 1, 2,..., n.

Obtained EII enables the ranking of products, and their prototypes based on their environmental impact in LCA. The top position in the ranking corresponds to the minimum EII value, where a lower EII value indicates a smaller negative environmental impact.

3.4 Stage 4: Determination of the Social Responsibility Index (SRI)

Research design assumes that product improvement will also consider the fulfilment of social responsibility standards. This derives from the concept of sustainable enterprise development, where it is essential for companies to take actions based on a shared understanding of social responsibility. Social responsibility according to ISO 26000 [74] is defined as the impact of a company's decisions and actions on society through transparent and ethical behaviours across seven core areas: organizational governance, human rights, labour practices, environment, fair operating practices, consumer issues, and community involvement and development.

Various approaches exist in our fields of research (management, production engineering), e.g.: social innovation design [75], which emphasizes the role of designers, or transformation design [76], focusing on designing within social transformation in a local context. These approaches confirm that designers can directly and indirectly encompass social responsibility in their products, processes, and services. Social responsibility within products is derived from individual ethical values of designers [77], as well as customer needs, including engagement of other enterprise stakeholders, e.g., through Corporate Social Responsibility (CSR) [78]. In our model, social responsibility specifically pertains to Socially Responsible Design (SRD) [79].

SRD focuses on alleviating societal problems to improve the quality of life through intentional design. During socially responsible design, it is necessary to address macro-social issues (e.g., health, governance, education, crime, fair trade, social inclusion, and economic policy) and macro-environmental requirements (poverty, energy, climate change, rapid population growth, etc.) [78]. For manufacturing enterprises, decisions involving social responsibility should be made as early as possible in the product engineering process, ideally during product design – to increase the likelihood of cost reduction and efficiency. This is achieved by understanding the societal impacts of offered products and how changes in these products can contribute to sustainable production [77 ,80].

In this regard, we propose the Social Responsibility Index (*SRI*) for products and their prototypes, calculated through steps 4.1-4.3 described below and conducted by team of experts. They are selected independently [47, 48]. The number of experts vary from 6-8 [49], 4-15 [50], or 10 [51] experts. According to [81], fewer experts in the team are beneficial because a collective opinion leads to fewer socially responsible decisions resulting from an increase in the moral leeway of their opinions. Experts should also come from various disciplines (interdisciplinary collaboration) [77] and include: i) de-signers from the model applicating enterprise; ii-a) CSR experts from the company, or, in a more ambitious approach, ii-b) experts in Sustainable Development Goals (SDGs) from relevant NGOs. Such a team composition assures a socially responsible approach to business, including defining a sustainable development perspective and supporting sustainable production and consumption analyses [75-77, 79].

- Step 4.1. Identification of the social responsibility criteria

The model design focuses on evaluating products and their prototypes by assessing the importance and feasibility of social responsibility criteria. These criteria are selected by a team of experts and are based on six areas specified in ISO 26000, excluding the environmental area as it is addressed in the third stage of the model [74]: i) Organizational governance; ii) Human rights (due diligence; human rights situations at risk; avoidance of complicity; resolving grievances; discrimination and vulnerable groups; civil and political rights; economic, social, and cultural rights); iii) Labour practices (employment and working relationships; working conditions and social protection; social dialogue; occupational health and safety; employee training and development); iv) Fair operating practices (anti-corruption measures; responsible political engagement; fair competition; promoting social responsibility in value chains; respect for property rights); v) Consumer issues (fair marketing, factual and impartial information, and fair contractual practices; consumer health and safety protection; sustainable consumption; customer service, support, complaint resolution, and dispute settlement; consumer data protection and privacy; access to basic services; education and awareness); vi) Community involvement and development (community engagement; education and culture; job creation and skills development; development and access to technology; wealth and income creation; health; social investments).

Analysing all social responsibility criteria is inefficient, as many may be irrelevant to the overall assessment of a product's or prototype's social responsibility [45]. Therefore, the selected social criteria should specifically relate to the target product (research subject) and establish a strong connection to fulfilling social responsibility objectives [46].

The selection process for these criteria is carried out by an expert team using methods such as focus groups or alternative approaches like PCR [54]. To ensure consistency in the criteria analysis throughout the model, the total number of social responsibility criteria should ideally fall within the range of 7±2 [46], aligning with the number of qualitative criteria used in Stage 2.

- Step 4.2. Grading of the social responsibility criteria

The social responsibility criteria selected in Step 4.1 are subjected to significance grading. Experts evaluate these criteria based on their relevance to overall customer satisfaction with the product.

The importance of each criterion is rated using a five-point Likert scale [62], where: 1 – criterion irrelevant, 5 – most important criterion.

The weight (g_i) of each social responsibility criterion is then calculated as the arithmetic mean of the importance ratings assigned to that criterion.

- Step 4.3. Evaluation of the degree of accordance with social responsibility standards

The analysed product and its prototypes are assessed for their compliance with social responsibility standards. Ratings are assigned by an expert team using a scale from 0 to 1 [82], where: 0 indicates the criterion does not meet social expectations; 1 indicates full satisfaction of social expectations; and 0.7 denotes acceptable fulfilment of social expectations [55, 57].

Focus groups [51] are often employed for assigning these ratings. The evaluation is conducted based on the social responsibility criteria identified in Step 4.1. Simultaneously, analysing the qualitative criteria parameters (from Stage 2 of the model) that may influence the social responsibility fulfilment of the product and its prototypes is beneficial.

Assessing socially responsible products is inherently linked to uncertainty, including epistemic uncertainty regarding actual consequences and ethical uncertainty concerning the purpose of the evaluation [77, 80]. This ambiguity arises from questions about whether the outcomes of socially responsible products will be desirable, particularly if they introduce potential disadvantages for stakeholders, such as increased prices or reduced usability compared to alternative solutions.

To reduce this uncertainty, the proposed model incorporates an analysis of the potential negative effects of social responsibility initiatives [77, 80]. Expert assessments of social expectation fulfilment can be supported by supplementary questions, such as those proposed in [83, 84]. Achieving a comprehensive assessment of social responsibility fulfilment in verified products and prototypes requires ethical conduct by the expert team. Additionally, the process encourages the integration of sustainable design practices—an ongoing global challenge [82].

After assessing the social responsibility fulfilment, the *SRI* is determined for the product and its prototypes, considering the importance of social responsibility criteria (identified in Step 4.2.). The *SRI* index is based on the concept proposed in [43], adopting the Coverage of Fulfilment method. This method distinguishes between fulfilment coverage for different social criteria and total coverage for these criteria across the analysed products and prototypes. Initially, the Total Coverage for each social criterion (*OP*) is calculated for the product and its prototypes, considering the importance of these criteria (Eq. 3):

$$OP_i = \sum g_i \frac{ps_i}{rs_i} \tag{3}$$

where: ps_i – the number of positive grades (value = 1) of fulfilment of social responsibility standards for per criterion; rs_i – the total number of all grades per criteria within the fulfilment of social responsibility standards; g_i – criterion weight; i – product or prototype, $i = 1, 2,\dots, n$.

Subsequently, the *SRI* is determined for a given product and prototype (Eq. 4):

$$SRI_i = \sum OP_i \tag{4}$$

where: OP_i – total coverage for social criteria of the i-th product or its prototype; i – product or prototype, $i = 1, 2,\dots, n$.

The *SRI* allows to create a ranking of products or their prototypes in terms of accordance with social responsibility standards. Higher *SRI* values indicate a more favourable level of this index.

3.5 Stage 5: Calculation of the aggregated Quality-Environment-Social-Responsibility Indicator (QESR)

The model aims to determine the most favourable direction for product development, considering its quality, environmental impact throughout the life cycle, and fulfilment of social responsibility standards. Therefore, at this stage of the model, the *AQI*, *EII,* and *SRI* are aggregated into a single composite Quality-Environment-Social-Responsibility Indicator (*QESR*).

It is assumed that each index determined within the model, *AQI*, *EII*, and *SRI*, is a normalized index. This is necessary to standardize these index values into a unified and comparable measure [85], given the inability to standardize the values of an LCA index, where the value does not have an upper boundary limit. Therefore, this relativization (normalization) is necessary and consequently requires appropriate actions on the quality and social indices. The proposed relativization is applicable if the total number of analysed products meets the principle of a minimum of 7±2 products [46].

Initially, the normalized *AQI* for the *i*-th product or prototype is calculated (Eq. 5):

$$w_{ji} = \frac{AQI_{max} - AQI_i}{AQI_{max} - AQI_{min}} \tag{5}$$

where: w_{ji} – normalized *AQI* for the i-th product or prototype; AQI_{max} – highest quality; AQI_{min} – lowest quality (both max and min can be calculated with any method, but consequently the same throughout the whole *QESR* application); *i* – product or prototype, *i* = 1, 2,…, *n*.

Then, the normalized *EII* is calculated (Eq. 6):

$$W_{si} = \frac{EII_{max} - EII_i}{EII_{max} - EII_{min}} \tag{6}$$

where: ws_i – normalized *EII* for the i-th product or prototype; EII_{max} – highest LCA value; EII_{min} – lowest LCA value; *i* – product or prototype, *i* = 1, 2,…, *n*.

Then, the normalized *SRI* is calculated (Eq. 7):

$$w_{pi} = \frac{SRI_{max} - SRI_i}{SRI_{max} - SRI_{min}} \tag{7}$$

where: wp_i – normalized *SRI* for the i-th product or proto-type; SRI_{max} – highest *SRI* value, SRI_{min} – lowest *SRI* value; *i* – product or prototype, *i* = 1, 2,…, *n*.

Then, the aggregated *QESR* indicator is calculated as in Eq. 8:

$$QESR_i = \frac{\alpha w_{ji} + \beta w_{si} + \gamma w_{pi}}{\alpha + \beta + \gamma} \tag{8}$$

where: α – relevance of the quality component; β – relevance of the environment component; γ – relevance of the social responsibility component; w_{ji} – normalized *AQI*; w_{si} – normalized *EII*; w_{pi} – normalized *SRI*; *i* – product or prototype, *i* = 1, 2,…, *n*.

Then, considering the normalized indexes, their weights can be adjusted in the process of calculating the aggregated index. The weights of each aspect are assigned collectively by experts from teams selected in stages 2, 3, and 4 of the model. It is possible to establish such weights [55, 86, 87], e.g. $\alpha = 7$, $\beta = 3$, $\gamma = 2$. In such a case the Eq. 9:

$$\alpha{:}\beta{:}\gamma{:}\delta{=}7{:}3{:}2 \tag{9}$$

It should be noted that the change of adopted ratios between the indexes would result in changes in the final hierarchy of decision alternatives. Hence, the model is sensitive to the weights of normalized indexes.

The total weight sum does not have to equal 1, allowing for considerable flexibility in determining the weight proportions. The aggregated *QESR* indicator is calculated with use of Eq. 10:

$$QESR_i = 1 - \left(0.083\left(7w_{ji} + 3w_{si} + 2w_{pi}\right)\right) \tag{10}$$

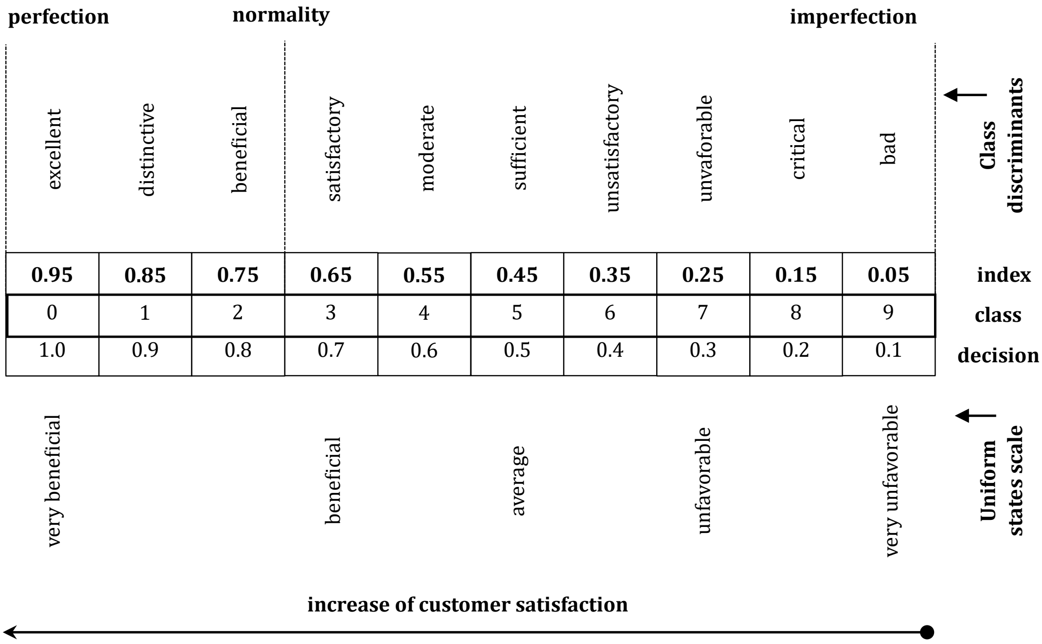
where: w_{ji} – normalized *AQI*; w_{si} – normalized *EII*; w_{pi} – normalized *SRI*; *i* – product or prototype, *i* = 1, 2,…, *n*.

The *QESR* indicator is interpreted as follows: i) from a qualitative perspective, it represents the level of customer satisfaction with using the product; ii) from an environmental perspective, it indicates the potential for achieving a product that is environmentally friendly throughout its lifecycle, depending on the analysed environmental impacts; iii) from a social perspective, it signifies the fulfilment of societal expectations within the product. A higher *QESR* indicator value reflects a closer-to-perfect level of the three analysed aspects simultaneously.

3.6 Stage 6: Elaboration of a product ranking under the aggregated QESR Indicator

Based on the Quality-Environment-Social-Responsibility (*QESR*) indicator, a ranking of products (or their alternatives) is created. Products should be ordered from highest to lowest *QESR* value. A higher *QESR* value indicates a more favourable index and higher customer satisfaction level. Therefore, the top position in the ranking corresponds to the maximum *QESR* value and represents the product that is most desired in terms of quality, environmental impact, and social responsibility. The verbal interpretation of the *QESR* indicator is conducted on a relative scale (Fig. 5).

The *QESR* indicator can help improving products, i.e. a prototype with the maximum *QESR* value will best meet customer expectations in terms of quality, while also having a minimal negative environmental impact in its entire life cycle, at the same time keeping the social responsibility standards.



0.95	0.85	0.75	0.65	0.55	0.45	0.35	0.25	0.15	0.05	index
0	1	2	3	4	5	6	7	8	9	class
1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	decision

Fig. 5 Interpretation scale of the QESR indicator: customer satisfaction with the products in terms of quality, environmental impact, and social responsibility [51, 60].

4. Results

Light Passenger Vehicles (LPVs) of a global manufacturer were employed as study subject. They are pivotal in mitigating climate change due to their energy efficiency and reduced environmental impact during use [88]. The analysis focused on a Hybrid Electric Vehicle (HEV) [89], which proves to be a promising solution for fuel savings, moderating fuel costs for consumers, and aiding in pollution reduction while meeting environmental regulations. The key advantage of HEVs lies in their drivetrain, which re-duces fuel consumption through an electric motor (EM) to achieve the required vehicle power. The electric motor utilizes energy from a battery or regenerative braking to power auxiliary systems and minimize engine idling [90]. A detailed characterization of HEVs is presented, for instance, in [91]. Moreover, hybrid vehicles are widely recognized and utilized globally, thus meeting model assumptions. Due to the research's specificity, the analysed HEV is seen as a reference vehicle, or a generalization of vehicles of this type [32].

For Stage 1 of the model, the research goal was established for the selected subject of study: determining the most favourable direction for improving HEVs through proposed manufacturing alternatives (prototypes), considering their: i) quality, ii) environmental impact throughout their lifecycle, and iii) meeting the social responsibility standards.

In Stage 2 a team of five experts undertook the task of defining a quality index for HEV and its prototypes. Initially, quality criteria were established to internally conceptualize quality perception. The selection process was guided by broad categories of quality criteria outlined in ISO/IEC

25010 [43], the HEV catalogue (specification), and quality criteria proposed by other authors (e.g., [90-93]. The primary quality criteria chosen for verification included: total mass (kg), maximum engine power (kW), maxi-mum speed (km/h), battery range (km), battery charging time (hours), vehicle colour, vehicle dimensions (mm), equipment, fuel consumption (average), and drivetrain. The assumptions regarding the number of quality criteria, with a maximum of 10 and a minimum of 5 [46], were met.

Subsequently, all criteria were characterized based on their descriptive measures. For the reference HEV, the catalogue (specification) and current parameters of these criteria were utilized. Six design solution prototypes for the reference HEV were pro-posed. These prototypes were developed as modifications of the current states of the analysed HEV criteria. According to the proposed model concept, the Pareto-Lorenz principle (20/80) was applied in this process. Seven design solutions were obtained (the current solution and its six modifications/alternative design solutions), as shown in Table 2.

Table 2 Characteristic of reference HEV criteria and its prototypes

Alternative	C1	C2	C3	C4	C5
Ref. product	1815	140	200	1195	≈30 min
Prototype 1	2178	84	220	1434	> 30 min to 3 h
Prototype 2	2541	112	240	1673	> 3 h to 6 h
Prototype 3	2904	168	260	1912	> 6 h to 9 h
Prototype 4	3267	196	180	2151	> 9 h to 12 h
Prototype 5	1452	224	160	956	> 12 h to 15 h
Prototype 6	1089	252	140	717	> 15 h
Alternative	**C6**	**C7**	**C8**	**C9**	**C10**
Ref. Product	white pearl	4630 × 1780 × 1435	basic	4.40	front axis
Prototype 1	clean white	5556 × 2136 × 1722	advanced	5.28	rear axis
Prototype 2	light grey	6482 × 2492 × 2009	full	6.16	AWD
Prototype 3	dark grey	7408 × 2848 × 2296	advanced	7.04	4 × 4
Prototype 4	black	3704 × 1424 × 1148	basic	7.92	front axis
Prototype 5	red	2778 × 1068 × 861	full	3.52	rear axis
Prototype 6	white pearl	1852 × 712 × 574	basic	2.64	4 × 4

C1: total mass (kg); C2: maximum engine power (kW); C3: maximum speed (km/h); C4: battery range (km); C5: battery charging time (hours); C6: vehicle colour; C7: vehicle dimensions (mm); C8: equipment; C9: fuel consumption (average) (l); C10: drivetrain.

To assess the quality of HEV and its prototypes, customer expectations were gathered through a survey conducted as a pilot study to verify the proposed model concept. The survey was conducted in March and April 2024 among 116 randomly selected customers who use LPVs. Pilot studies [94, 95] proved this sample size to be sufficient. The survey was administered electronically through Microsoft Forms. The response rate for the survey was 100 %, and the collected data complete. This resulted from the form of pilot studies, which were conducted in a targeted (non-random) manner to specific customers who had previously expressed a willingness to participate in the survey. Additionally, the studies were carried out in-depth by utilizing direct communication techniques with customers. This involved obtaining surveys during direct interviews, which aimed to identify potential difficulties in completing the survey (understanding the survey questions). Simultaneously, the use of a computer tool aided in avoiding mistakes regarding skipping a question or a required response. In the survey, customers rated the importance of selected vehicle criteria on a Likert scale and evaluated the quality fulfilment of these criteria based on the proposed design alternatives.

Based on the acquired ratings of criterion weights for the reference HEV, the im-portance and quality of criteria were determined by calculating the arithmetic mean of these ratings. Following the developed model, Eq. 1 was utilized to calculate the *AQI* for reference vehicle and its prototypes (Table 3).

Table 3 Relevance of the quality criteria for the HEV and ranking of HEV

No.	Quality criteria	Criterion weight	Quality of criteria for HEV and its prototypes						
			Ref.	P1	P2	P3	P4	P5	P6
C2	maximum engine power (KM)	4.09	3.66	2.07	2.76	3.75	4.06	4.33	4.33
C4	battery range (km)	4.18	3.37	3.71	4.00	4.33	4.47	2.46	2.04
C5	battery charging time (h)	4.09	4.57	3.83	2.76	2.24	1.81	1.46	1.30
C9	fuel consumption (average) (l)	4.21	4.47	4.11	3.61	3.19	2.98	4.63	4.68
C3	maximum speed (km/h)	3.86	3.97	4.17	4.27	4.28	3.33	2.70	2.33
C7	vehicle dimensions (mm)	3.43	3.51	3.23	2.92	2.75	3.60	3.34	2.86
C8	equipment	3.84	3.31	4.44	4.70	4.44	3.31	4.44	3.31
C10	drivetrain	3.85	3.99	3.82	3.84	4.64	3.99	3.82	4.64
C1	total mass (kg)	2.95	3.66	3.36	3.09	2.74	2.36	3.34	2.90
C6	vehicle colour	2.74	3.82	3.56	3.75	3.97	4.42	3.39	2.49
	AQI		3.81	3.64	3.58	3.65	3.43	3.39	3.12
	Ranking		1	3	4	2	5	6	7

AQI ranks the utility of the reference HEV and its prototypes. It was observed that the reference vehicle performed best. However, the ranking may be reversed in further stages of model application, when considering environmental impact and social responsibility.

In Stage 3, the *EEI* of the HEV throughout its life cycle was determined. A second level LCA was conducted under ISO 14040 rigor [64], utilizing GREET v1.3.0.13991 software data [96], covering material extraction and processing, production, usage, and recycling.

The functional unit was defined as the vehicle traveling 150,000 km [89, 97, 98]. This unit allowed for data normalization to facilitate comparison with vehicle prototypes. However, the functional unit could vary, e.g. [99] proposes 200,000 km. The system boundaries were set within the timeframe of 2021-2024 and data from the GREET model.

The first phase of LCA included carbon dioxide (CO_2) from material extraction and processing in vehicle component construction, involving extraction, smelting, beneficiation, and refining [100]. Following [101], CO_2 emissions in this initial phase are calculated with Eq. 11:

$$\begin{cases} C_M = \sum_x \left(C_{x,f} + C_{x,e}\right) \\ C_{x,f} = m_x \sum_n \left[E_{x,n} \sum_k \omega_{x,n,k} \alpha_k\right] \\ C_{x,e,} = m_x \sum_n \left(\frac{E_{x,n}\omega_{x,n,e}}{3600}\right) \end{cases} \tag{11}$$

where: $C_{x,f}$ – CO_2 emission from fuel consumption at material production; $C_{x,e}$ – CO_2 emission from electricity consumption at material production; x – material; m – weight (kg); n – production process; $E_{x,n}$ – energy consumption per material unit in its production process (kJ/kg); k – fuel; $\omega_{x,n,k}$ – share of fuel consumption in $E_{x,n}$; $\omega_{x,n,e}$ – share of electricity consumption in $E_{x,n}$; α_k – CO_2 emission factor from fuel consumption (CO_2kg/kJ).

Main materials in HEV production were identified, excluding low mass materials. Emissions during the processing of these materials were specified according to the literature [102] (Table 4). Data from the GREET model and [100, 101] results allowed us to adopt the energy consumption coefficient for material production and the CO_2 emission factor for energy consumption in the entire life cycle. In this way, CO_2 emissions from the material extraction and processing phase for the analysed reference vehicle were calculated (Table 4). The total CO_2 emissions during the material extraction and processing phase for the HEV amounted to 623.19 kJ = 0.623 MJ. It was inferred that fuel consumption emissions contributed significantly more to the total CO_2 emissions during the first LCA phase.

Table 4 Main materials in HEV production and CO_2 emissions

Material	Material (kg)	Emission factor of material production (CO_2/kg)	CO_2 emission from fuel consumption	CO_2 emission from electricity consumption	Total CO_2 emission
Steel	899.80	2.00	403.28	0.10	403.38
Iron	77.20	0.55	0.10	0.00	0.11
Cast aluminium	67.50	2.62	86.95	0.08	87.02
Wrought aluminium	27.60	5.92	76.15	0.07	76.22
Copper	57.90	2.35	25.20	0.02	25.22
Glass	35.80	1.62	1.95	0.00	1.95
Plastic	148.80	3.05	16.19	0.02	16.21
Rubber	23.40	3.62	403.28	0.10	403.38

Next, emissions resulting from vehicle and component production were analysed. This analysis focused on emissions during the processing and assembly of key com-ponents, with the possibility of additionally considering emissions during their distribution [100]. Following the methodology presented in [101], CO_2 emissions were calculated using Eq. 12:

$$\begin{cases} C_{VA} = \sum_{x} \left(C_{y,f} + C_{y,e} \right) + \dfrac{E_{VA}}{3600} \\ C_{y,f} = \sum_{q} \left[E_{y,q} \sum_{k} \omega_{y,q,k} \alpha_k \right] \\ C_{y,e,} = \sum_{q} \left(\dfrac{E_{y,q} \omega_{y,q,e}}{3600} \right) \end{cases} \tag{12}$$

where: C_{va} – CO_2 emission from vehicle components production; $C_{y,f}$ – CO_2 emission from fuel consumption at component production; $C_{y,e}$ – CO_2 emission from electricity consumption at component production; y – vehicle component (part); E_{va} – electricity consumption at vehicle assembly; q – production process; $E_{y,q}$ – energy consumption per component in its production process (kJ); $\omega_{y,q,k}$ – share of fuel consumption in $E_{y,q}$; $\omega_{y,q,e}$ – share of electricity consumption in $E_{y,q}$; α_k – CO_2 emission factor from fuel consumption (CO_2kg/kJ).

GREET data and detailed characteristics of the vehicle production process allowed us to estimate the energy consumption and CO_2 emission levels when producing components for the reference HEV (Table 5). The assembly of the main components is assumed to consume approximately 862 MJ of energy.

A crucial component of an HEV is the battery. In this analysis, a lithium-ion (Li-Ion) battery was examined, consisting of elements such as the cathode, anode, separator, electrolyte, packaging, and battery management system. Based on the GREET model and [98, 103, 104], a material list for this type of battery was assumed.

Table 5 Energy consumption and CO_2 emissions in the production process of an LPV

Production process	Energy (MJ)	CO_2 (kg)
material transformation	22912.60	1261.73
machining	1163.40	66.34
vehicle painting	4936.75	317.51
HVAC & lighting	3951.06	266.56
heating	3684.50	231.02
material handling	817.46	54.50
welding	1089.95	73.45
compressed air	1634.92	110.18

Additionally, based on studies presented in [98, 103, 104] and data from the GREET model, the energy consumption during the production of the Li-Ion battery was determined. The assembly of a Li-Ion battery consumes approximately 2.67 MJ/kg, resulting in about 1002 MJ for the entire battery. With Eq. 12, CO_2 emissions during the production and assembly of HEV components (including the battery) are estimated to be around 43,572.18 MJ.

Subsequently, an analysis of energy consumption and carbon emissions during the vehicle's usage phase, which constitutes the third phase of the life cycle, was conducted. This phase includes fuel consumption and vehicle maintenance [100]. Eq. 13 was applied [101]:

$$C_{VU} = \frac{dF_k}{100}(\rho_k \alpha_k LHV_k + C_k) \tag{13}$$

where: C_{vu} – CO_2 emission from vehicle exploitation; d – total distance driven (km); F_k – combustive fuel consumption (l/100 km); ρ_k – fuel viscosity; k – fuel; LHV_k – lower calorific value of fuel (kJ/kg); C_k – CO_2 emissions per k unit of fuel production.

The lifespan of an HEV is around 150,000 km [97], we assumed the use of PB 98 gasoline within standard specifications. Based on the manufacturer's characteristics, the average fuel consumption of the HEV is assumed 4.4 L/100 km, and the total driving range with a full tank and hybrid drive is up to 1000 km. Using Eq. 13, CO_2 emissions during the reference phase of HEV over its lifespan are estimated to be ap-proximately 470,969 MJ.

Next, an analysis of emissions during the recycling of selected HEV components was conducted. This pertains to the fourth phase of LCA — recycling, disposal, and reuse [99]. This phase includes disassembly, separation, and purification of metals and other non-metallic materials. Metals are recycled, while other materials like plastics and glass are typically landfilled or incinerated. For Li-Ion batteries, the recycling process includes cooling the battery, cutting, and shredding, separating, and sorting shredded material, converting lithium to lithium carbonate (or lithium oxide), neutralizing electrolytes to stable compounds, and, if applicable, recovering cobalt from lithium cobalt oxide [105]. CO_2 emissions in the fourth phase of LCA are estimated using Eq. 14 [101]:

$$\begin{gathered} C_{RE} = C_{re,f} + C_{re,e} \\ C_{re,f} = \sum_x \left[m_x E_{re,x} \sum_k \left(\omega_{re,x,k} \alpha_k \right) \right] \\ C_{re,e} = \left[\frac{E_{vd}}{3600} + \sum_x \left(m_x \frac{E_{re,x}\omega_{re,x,e}}{3600} \right) \right] \end{gathered} \tag{14}$$

where: C_{RE} – CO_2 emissions from vehicle recycling; $C_{re,f}$ – CO_2 emissions from fuel consumption during vehicle recycling; $C_{re,e}$ – CO_2 emissions from electricity consumption during vehicle recycling; $E_{re,x}$ – energy consumption per unit of material x in the recycling phase (kJ/kg); x – recycled material; $\omega_{re,x,k}$ – share of fuel consumption in $E_{re,x}$; $\omega_{re,x,k}$ – share of electricity consumption in $E_{re,x}$; m – weight (kg); E_{vd} – energy consumption during vehicle disassembly.

GREET data implies an assumption, that CO_2 emissions during the recycling of an HEV include approximately 630 kWh of electricity for disassembly, and for recycling the remaining components: 1114 kWh of electricity, 8.4 kWh of natural gas, and 10 kg of coal. Based on these assumptions and using Eq. 15, CO_2 emissions in the final phase of the LCA for the reference HEV are estimated to be 6608 MJ.

The total environmental impact in the LCA for the reference HEV was calculated with Eq. 15:

$$EII = C_M + C_{VA} + C_{VU} + C_{RE} \tag{15}$$

where: EII – EEI of the reference HEV in its entire life cycle; C_M – CO_2 emission from material extraction and processing; C_{va} – CO_2 emission from vehicle components production; C_{vu} – CO_2 emission from vehicle exploitation; C_{RE} – CO_2 emission from vehicle recycling.

The estimated CO_2 emissions over the life cycle of the analysed reference HEV are approximately 520,150 MJ. It was observed that the largest emissions occur during the vehicle's usage phase, followed by component production, recycling, and the smallest amount during material extraction and processing.

After assessing the reference HEV, an LCA of its prototypes was conducted under the assumptions of the model, i.e. using simplified modelling to reflect changes in LCA values based on changes in the parameters of HEV quality criteria, following the Pareto principle [73]. The prospective and simplified LCA of HEV prototypes was carried out using Eq. 5. The results are presented in Table 6.

Table 6 Prospective LCA of HEV prototypes

Alternative	EII [MJ]	Ranking
Ref. product	520150	3
Prototype 1	624180	4
Prototype 2	728210	5
Prototype 3	832240	6
Prototype 4	936270	7
Prototype 5	416120	2
Prototype 6	312090	1

Aggregated *EII* was obtained for the reference HEV and its prototypes over their life cycle. Vehicles were ranked, with Prototype 6 securing the top position, which anticipates its least negative total environmental impact.

Next, the *SRI* for the reference HEV and its prototypes was obtained, with participation of a multidisciplinary team of four experts, including CSR specialists and the authors of the article. Initially, HEV – relevant social responsibility criteria were selected from those presented in Step 4.3 of our model. Ultimately, nine main criteria belonging to six areas indicated in ISO 26000 were chosen: (CC1) fair competition – assessment of the possibility of applying fair (including unfair) competition by using very distant or remarkably similar product solutions as another manufacturer; (CC2) promoting social responsibility in the value chain – assessment of the ap-plication of a solution that can shape social attitudes; (CC3) access to essential services – assessment of the product or prototype functionality in terms of selected usability criteria; (CC4) technology development and access – assessment of the advancement and accessibility for customers of selected technological features; (CC5) social investment – assessment of the degree of implementation of pro-social investments in terms of usability criteria of the product or its prototype; (CC6) community involvement – assessment of differences between the product and prototypes in terms of initiating pro-social behaviours for the common good; (CC7) wealth and income creation – assessment of differences in basic technological features of the product and prototypes that affect the increase in customer satisfaction level from owning a given product/prototype compared to others; (CC8) sustainable consumption – assessment of the environmental-consumption balance in the form of achieving satisfaction from the most sustainable product solution or its prototypes; (CC9) education and awareness – assessment of the possibility of providing ap-propriate product or prototype solutions as a result of customer education and awareness.

Subsequently, the relevance of these criteria was assessed in terms of accordance to social responsibility standards. The highly relevant criteria (g1) were: fair competition (CC1), promoting social responsibility in the value chain (CC2), access to essential ser-vices (CC3), technology development and access (CC4), and sustainable consumption (CC8). The moderately relevant criteria (g2) were: community involvement (CC6), wealth and income creation (CC7), and social investments (CC5). The less important criterion (g3) was: education and awareness (CC9). Fixed weights were assigned to these criteria in the ratio 50:10:1 [55, 57].

Then, the reference HEV and its prototypes were evaluated for social responsibility compliance. The evaluations were conducted by a team of experts using a 0-1 scale, where scores equal to or above 0.7 indicated an acceptable level of compliance. The social responsibility compliance scores were then processed into binary values (0 - does not comply, 1 - complies). The results are presented in Table 7.

Table 7 Social responsibility compliance of reference HEV and its prototypes

Alternative	Level of social responsibility compliance by the decision criteria (0-1)								
	CC1	CC2	CC3	CC4	CC5	CC6	CC7	CC8	CC9
Ref. product	0.5	0.8	0.9	0.6	0.6	0.6	0.8	0.6	1.0
Prototype 1	0.6	0.7	0.8	0.8	0.6	0.7	0.5	0.5	0.9
Prototype 2	0.5	0.6	0.9	0.9	0.9	0.9	0.7	0.5	0.8
Prototype 3	0.7	0.5	0.9	0.8	0.9	0.7	0.5	0.5	0.7
Prototype 4	0.8	0.4	0.7	0.7	0.7	0.6	0.6	0.4	0.6
Prototype 5	0.5	0.9	0.6	0.7	0.6	0.8	0.9	0.8	0.5
Prototype 6	0.6	1.0	0.5	0.6	0.7	0.5	0.9	0.9	0.5
Alternative	Fulfilment of social responsibility standards by the decision criteria (0 or 1)								
	CC1	CC2	CC3	CC4	CC5	CC6	CC7	CC8	CC9
Ref. product	0	1	1	0	0	0	1	0	1
Prototype 1	0	1	1	1	0	1	0	0	1
Prototype 2	0	0	1	1	1	1	1	0	1
Prototype 3	1	0	1	1	1	1	0	0	1
Prototype 4	1	0	1	1	1	0	0	0	0
Prototype 5	0	1	0	1	0	1	1	1	0
Prototype 6	0	1	0	0	1	0	1	1	0

(CC1) fair competition; (CC2) promoting social responsibility in the value chain; (CC3) access to essential services; (CC4) technology development and access; (CC5) social investment; (CC6) community involvement; (CC7) wealth and income creation; (CC8) sustainable consumption; (CC9) education and awareness.

After assessing social responsibility compliance, an aggregated *SRI* was deter-mined for the reference HEV and its prototypes with use of Eq. 6 and Eq. 7 (Table 8).

The calculated *SRI* allowed to establish a ranking of the reference HEV and its prototypes in terms of social responsibility compliance. Prototype 3 secured the top position, with Prototype 5 closely following. The reference product performed the worst among the assessed models, though these results may vary depending on expert opinions.

Finally, an aggregated *QESR* indicator was determined (model – stage 5). This in-volved combining the quality (*AQI*), environmental (*EII*), and social responsibility (*SRI*) indexes into a single *QESR* indicator. The three abovementioned indexes indices were normalized with respect to the reference HEV and its prototypes, using Eq. 8, Eq. 9, Eq. 10. Eq. 11, Eq. 12, Eq. 13 served for the estimation of the aggregated *QESR* indicator, which resulted in a ranking of the reference HEV and its prototypes. The ranking proves Prototype 3 being the most favourable and Prototype 6 the least favourable. For a verbal interpretation of the results, a further analysis was conducted (Stage 6). A verbal relative scale was used for this purpose, with the final model results and in-depth analysis presented in Table 9.

Table 8 SRI for the reference HEV and its prototypes

Alternative	SRI	Ranking
Ref. product	12.33	7
Prototype 1	17.89	3
Prototype 2	14.56	5
Prototype 3	19.00	1
Prototype 4	17.78	4
Prototype 5	18.89	2
Prototype 6	13.33	6

Table 9 Aggregated QESR indicator for the reference HEV and its prototypes

Alternative	Normalized weighted AQI	Normalized weighted EII	Normalized weighted SRI	QESR	Interpretation	Ranking
Ref. product	0.00	2.00	2.00	0.67	satisfactory	3
Prototype 1	1.72	1.50	0.33	0.70	beneficial	2
Prototype 2	2.33	1.00	1.33	0.61	satisfactory	5
Prototype 3	1.62	0.50	0.00	0.82	distinctive	1
Prototype 4	3.86	0.00	0.37	0.65	satisfactory	4
Prototype 5	4.26	2.50	0.03	0.44	sufficient	6
Prototype 6	7.00	3.00	1.70	0.03	bad	7

Prototype 3 was identified as the most suitable in terms of quality, environmental, and social responsibility aspects. It is then rational to guide accordingly the design of the reference HEV. Should Prototype 3 not be financially viable for the company, the ranking points at the next highest-ranked product, i.e. Prototype 1. A comprehensive comparison of the results obtained at each stage of model application is summarized in Table 10.

It was observed that Prototype 3, identified as the most advantageous, ranked second in the quality index (*AQI*), first in social responsibility (*SRI*), and sixth in environmental impact (*EII*). The final development decisions were influenced by the as-signed weights to each aspect (quality, environment, social responsibility) in the ratios of 7:3:2 [55]). It was noted that quality and environmental impact had a greater influence on the final ranking, with a smaller contribution of social responsibility. This phenomenon is evident in the case of the reference product, which ranked third according to the *QESR* indicator. The in-depth analysis of the impact of model indexes on the final product ranking was verified through a sensitivity analysis presented in the Discussion section of the article.

Table 10 Comparison of model indexes and resulting prototype rankings

Alternative	AQI and prototype ranking		EII and prototype ranking		SRI and prototype ranking		Final QESR indicator and prototype ranking	
Ref. product	3.81	1	520150	3	2.00	7	0.67	3
Prototype 1	3.64	3	624180	4	0.33	3	0.70	2
Prototype 2	3.58	4	728210	5	1.33	5	0.61	5
Prototype 3	3.65	2	832240	6	0.00	1	0.82	1
Prototype 4	3.43	5	936270	7	0.37	4	0.65	4
Prototype 5	3.39	6	416120	2	0.03	2	0.44	6
Prototype 6	3.12	7	312090	1	1.70	6	0.03	7

5. Discussion

The research aimed to develop a multicriteria decision-making model for predicting the improvement direction of current products based on methodically verified prototypes (alternative production solutions) through a multidimensional framework encompassing key sustainable development aspects: product quality (customer satisfaction), environmental impact throughout the product's life cycle, and compliance to social responsibility standards. These aspects, whether considered separately or in combination, have already been subjects of previous research [11, 12, 14, 15, 17].

The proposed approach integrates three respective indicators (*AQI, EII, SRI*) into a single Quality-Environmental-Social-Responsibility (*QESR*) indicator, providing a comprehensive assessment method. This integration represents the model's primary originality and its contribution to the field of management, sustainable development and production engineering, as corroborated by [4, 5, 9, 118], which responds to the ongoing challenges in sustainable product design. The developed *QESR* indicator aims to guide product development through personalized rankings of product prototypes, which remains a valuable approach for exploring new product opportunities or enhancing existing ones [106-109; 119-120].

The model's effectiveness was tested using HEV as a case study. The resulting prototype rankings aligned with the outcomes of each stage of the model, confirming the appropriateness of the chosen methodology. Consequently, a sensitivity analysis of the model was deemed necessary. This analysis aimed to verify the significance of the quality (*AQI*), environmental impact (*EII*), and social responsibility (*SRI*) indexes on the aggregated *QESR* indicator.

The sensitivity analysis was conducted using machine learning in Statistica 13.3 software. The input variables (independent) were the *AQI*, *EII*, and *SRI* values obtained from the model test for the reference HEV and its prototypes. The sensitivity analysis was performed twice: a) for unweighted relativized values, and b) for weighted relativized values, to additionally verify the impact of aspect weights on the final *QESR* ranking.

The sensitivity analysis was conducted using machine learning tools, specifically regression analysis, suitable for quantitative data. Random sampling was applied, with the following sample sizes: 70 % for training, 15 % for testing, and 15 % for validation [110, 111]. The initial value of the random generator was set to 1000. The search focused on identifying a Multilayer Perceptron (MLP) network with a minimum of 3 and a maximum of 10 hidden layers. Twenty networks were trained, retaining the five with the most favourable learning parameters each time.

For processing the relativized (unweighted) model indexes in the neural network, the most optimal set of networks was generated, from which the MLP 3-10-1 network was selected. This network had three input neurons, ten hidden layer neurons, and one output neuron. In contrast, for processing the relativized weighted model indexes, the MLP 3-6-1 network was chosen, featuring three input neurons, six hidden layer neurons, and one output neuron.

Based on the developed neural network models and the specified input and output data, a global sensitivity analysis was conducted. Global sensitivity analysis for the analysed model indicators for unweighted normalized indexes were: AQI=7.609, EII=24.641, SRI=8.999, and for weighted normalized indexes were: AQI=1.997, EII=8.7675, SRI=4.857. The interpretation of global sensitivity analysis results boils down to identifying input variables with values above 1, indicating significant influence on the output variable (including model quality) [112]. It was observed that in both cases, all analysed indicators AQI, EII, and SRI significantly impacted the aggregated $QESR$ indicator. In the global sensitivity analysis for unweighted relative indicators, the pre-dominant influence on the final $QESR$ indicator (including the final product ranking) was the EII indicator (24.641). Subsequently, the SRI indicator (8.999) had a significant but notably smaller impact, followed by the AQI indicator (7.609). Sensitivity analysis for weighted relative indicators revealed the impact of weights assigned to these indicators on the final ranking (including $QESR$), leading to approximate alignment of model indicator values. The conducted sensitivity analysis demonstrated that all ana-lysed indicators significantly influenced the final model outcome, confirming the validity and effectiveness of the developed model and research methodology. It was shown that weighting qualitative, environmental, and social aspects significantly affects the final model indicator ($QESR$), and consequently, the final ranking of products and their prototypes. Therefore, these weights should be thoughtfully assigned based on the needs of the model user, business development strategies, legal regulations, or market dynamics.

The main limitation of the model is the lack of direct consideration of customer preferences in the decision-making process at the environmental impact assessment stage in the product lifecycle, as well as in the assessment of social responsibility compliance. Nevertheless, it is justified to conduct these assessments by a competent and qualified expert team [49, 52, 53]. Another significant limitation is the limited access to data or the lack of assurance of comparability of results obtained from LCA – which is a widely known and discussed issue of LCA methodology [113,114]. Despite this limitation we still decided to employ LCA in our model, as it is currently considered to be the most popular and most efficient method for estimating the environmental impact of products throughout their life cycle [115-117]. Another limitation is the potential for divergent interpretations of social responsibility (not always synonymous with CSR), which also concern the diversity of socially responsible business practices, leading to varying model outcomes depending on the country or region of application. Consequently, this limits the comparability of model results when applied in culturally diverse markets.

Future research aims to consider incorporating customer feedback at the environmental impact analysis stage. Additionally, the model structure allows for further development with other indicators and sustainable development criteria. Addressing the model limitations, efforts will be made to establish assumptions enhancing the accuracy and reliability of environmental impact assessment. Further studies will also involve other products to ensure the universality of the developed model.

6. Conclusion

In the era of dynamic customer expectations, including concerns about global warming, adapting products to market and societal needs is crucial. However, achieving sustainable product development remains challenging. Therefore, the aim of this re-search was to develop an MCDM model for predicting the direction of improving cur-rent products towards prototypes (alternative production solutions) methodically verified in a multidimensional approach covering key aspects of sustainable development: quality, environmental impact throughout the life cycle, and social responsibility. The model was tested for a specific type of LPVs the HEVs.

Initially, the *AQI* was determined, requiring the identification of the vehicle's main quality criteria: total mass, maximum engine power, maximum speed, battery range, battery charging time, vehicle colour, vehicle dimensions, equipment, fuel consumption, and drivetrain. These criteria were modified by proposing six alternative design solutions (prototypes). Through survey research, expectations from 116 customers were obtained and processed, resulting in the *AQI*. According to this index, the reference product and its prototypes were ranked, with Prototype 1 deemed the most favourable in terms of quality. Next, the *EII* throughout the life cycle was determined. This involved conducting an LCA "from cradle to grave" according to ISO 14040 and using data from the GREET v1.3.0.13991 software. LCA results were employed for the prospective environmental impact assessment of the reference HEV and its prototypes, resulting in the *EII* index, which formed the basis for ranking these products. Prototype 6 showed the least negative environmental impact.

Subsequently, the *SRI* was determined. Selected social criteria from the ISO 26000 set were: fair competition, promoting social responsibility in the value chain, access to essential services, technology development and access, social investment, community involvement, wealth and income creation, sustainable consumption, education, and awareness. These criteria were assessed on a Likert scale for the reference HEV and its prototypes for relevance and social responsibility compliance. *SRI* resulted in a ranking, with Prototype 3 on top.

Finally, *AQI*, *EII* and *SRI* were aggregated into a single *QESR* indicator, considering their relativization and weighting. The indices were interpreted qualitatively and quantitatively on a relative scale. Ultimately, Prototype 2 was selected as possibly the most favourable in terms of quality, environment, and social responsibility aspects. In line with the model concept, it provides a good basis for determining the development direction of the reference HEV. Thus, the model test confirmed its effectiveness in prospectively deter-mining product development directions in accordance with the principles of sustainable development.

The model is dedicated to managerial decision-making in product design and production management. Therefore, it can support individuals, companies, and public entities in sustainable product development decisions, aiming to achieve socially re-sponsible production engineering that also ensures high product quality and environ-mental friendliness.

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