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## A METHOD TO EVALUATE THE LIFE CYCLE SUSTAINABILITY VALUE OF ALTERNATIVE SOLUTION DESIGNS

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**Abstract:** The paper focuses on developing an integrative methodology to evaluate environmental, economic, and social sustainability of alternative solution design options. Core approach is to extend the classic method of Quality Function Deployment (QFD) towards a holistic integrated model to overall evaluate the different aspects of all three pillars of sustainability (economy, ecology and social) across the product life cycle. The methods identify key aspects and allow users to consider and weigh different life cycle aspects in a overall scoring scheme.

**Keywords:** Life Cycle Evaluation (LCE), House of Quality (HQ), Quality Function Deployment (QFD), sustainability.

### 1. INTRODUCTION

Sustainability has emerged as a critical topic in contemporary discourse, particularly considering increasing environmental challenges and social responsibilities. The urgency of addressing climate change has been underscored by scientific evidence indicating that the Earth has experienced a significant temperature increase, largely due to greenhouse gas emissions from various sources, including transportation and industrial activities [1]. This climatic shift has resulted in more frequent and severe weather events, such as floods and heatwaves, which pose significant risks to human life and ecosystems [2]. Such initiatives highlight the growing recognition of the need for sustainable practices that not only mitigate environmental degradation but also promote social equity. The recent introduction of the Supply Chain Act in Germany exemplifies this trend, mandating companies to ensure respect for human rights within their supply chains [3].

This legislation reflects a broader shift towards integrating social and environmental considerations into business operations, driven by both regulatory frameworks and consumer demand for sustainable products.

The interplay between economic growth, environmental protection, and social responsibility is complex and often fraught with conflict. As businesses strive to achieve economic objectives, they must also navigate the challenges of implementing sustainable practices that address ecological concerns and uphold social rights [4-7]. The concept of the Triple Bottom Line (3BL, see Figure 1) emphasizes the need for a balanced approach that considers economic, environmental and social dimensions in decision-making processes [8-10].



Fig. 1. The interconnection of the elements of the Triple Bottom Line concept [5].

While the goal of sustainability is to achieve a balance between these dimensions, conflicts of interest often arise due to the differing priorities and objectives of various stakeholders.

One of the primary conflicts in sustainability is between environmental protection and economic growth. Companies are often driven by the need to maximize profits and shareholder value, which can lead to practices that are detrimental to the environment. For example, the use of non-renewable resources and the emission of greenhouse gases are common in many industries, despite their negative impact on the environment. On the other hand, implementing environmentally friendly practices can be costly and may reduce a company's competitiveness in the short term [11].

Another significant conflict is between social equity and economic efficiency. Ensuring fair labor practices, equitable distribution of resources, and respect for human rights are essential components of social sustainability. However, these practices can increase operational costs for companies, leading to higher prices for consumers and potentially lower profits. This conflict is particularly evident in global supply chains, where companies may face pressure to reduce costs by outsourcing production to countries with lower labor standards [12].

In conclusion, while conflicts of interest in sustainability are inevitable, adopting integrative methodologies that consider all dimensions of sustainability can help mitigate these conflicts and promote a more balanced approach to sustainable development.

However, finding effective compromises that satisfy all three aspects remains a significant challenge, as stakeholders across various sectors increasingly recognize the interconnectedness of these issues, the pursuit of sustainable development becomes not only a moral imperative but also a strategic necessity for long-term viability and success.

Regarding the Paris Climate Agreement and the Supply Chain Act, countries may in the future force local companies to integrate environmental and social aspects into their business operations. In addition, the consumer is more and more interested in buying sustainable

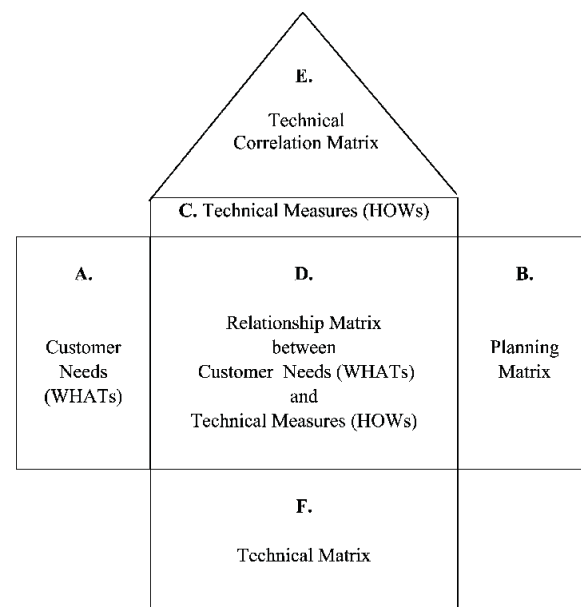
products and partly already integrates this into his purchase decision [13, 14].

## 2. THE HOUSE OF QUALITY AND THE QUALITY FUNCTION DEPLOYMENT

The House of Quality (HQ) is a fundamental component of QFD, a structured methodology used to transform customer requirements into specific technical features and quality characteristics for a product or service. QFD was first developed in Japan in the late 1960s and has since become a widely adopted tool in various industries for enhancing product development processes [15].

The HQ (Figure 2) is essentially a matrix that helps teams visualize the relationship between customer desires and the company's ability to meet those desires through technical specifications. The matrix is divided into several sections, each representing different aspects of the product development process. The primary sections include customer requirements, technical descriptors, relationship matrix, and competitive assessment [16].

- Customer Requirements lists the needs and expectations of the customers, often referred to as the "Voice of the Customer." These requirements are gathered through various means such as surveys, interviews, and market research;



**Fig. 2.** The model of "The House of Quality" [16].

- Technical descriptors are the engineering characteristics or technical specifications that correspond to the customer requirements. They represent the company's response to fulfilling the customers' needs;
- Relationship Matrix, part of HQ, shows the correlation between customer requirements and technical descriptors. It helps identify which technical features have the most significant impact on meeting customer needs;
- Competitive Assessment section compares the company's product with those of competitors, highlighting areas where the company excels or needs improvement.

The primary goal of QFD and the HQ is to ensure that customer requirements are systematically integrated into every stage of the product development process. This approach not only enhances customer satisfaction but also improves the overall quality and competitiveness of the product [17].

In recent years, the application of QFD has expanded to include considerations of sustainability. For example, the Green QFD-II model incorporates environmental and social aspects into the traditional QFD framework, allowing for a more holistic evaluation of new products or product variants based on ecological, economic, and social criteria [18].

### 3. LITERATURE REVIEW

A literature analysis has revealed that there are already good integrative approaches that implement at least partial aspects of the 3BL objectives. Masui et al. [19], for example, provide an excellent approach with the Quality Function Deployment for Environment model, which, however, leaves out costs over the product life cycle and is not very modular. Roach [14] also prepares the principle of QFD well on a theoretical level and even invokes the three pillars of sustainability. Unfortunately, this model lacks a concrete approach or methodology. Cagno et al. [20] also present a useful model that could theoretically even be extended in a modular way. For example, the Green Quality House used here could be

extended to include other aspects, such as cost or social. However, this could quickly become confusing, as it would result in a huge house. In addition, this model has the disadvantage that the authors do not take costs into account.

Looking at the classic, non-integrative QFD models, it is quickly apparent in the reviewed literature that the scheme is often identical. There are no intended approaches for the parallel integration of all sustainability aspects. Integrative models implement such aspects partially, but not completely – if so, they do not offer a usable methodology to evaluate product features by their sustainability aspects or leave out costs or social aspects over the product lifetime. In their Green QFD-II, Zhang et al. [23] includes Life Cycle Assessment and Life Cycle Costing in their QFD model. Thus, two of the three pillars of sustainability are already mapped, only the social component is missing.

The comparison of the examined literature indicates that the modularity of this approach is a major advantage, which will allow us to integrate further aspects (e.g., the evaluation of social aspects over a solution's life cycle) [27, 28].

Table 1

**Literature overview QFD models.**

| Author                    | Environmental | Economic | Social | Methodology |
|---------------------------|---------------|----------|--------|-------------|
| Roach (2014) [14]         | X             | X        | X      | -           |
| Cagno et al. (2007) [20]  | X             | -        | -      | X           |
| Masui et al. (2003) [19]  | X             | -        | -      | X           |
| Tursch et al. (2015) [21] | -             | -        | -      | X           |
| El Badoui (2022) [22]     | -             | -        | -      | X           |
| Zhang et al. (1999) [23]  | X             | X        | -      | X           |
| Hering et al. (2022) [24] | -             | -        | -      | X           |
| Gupta et al. (2012) [25]  | -             | -        | -      | X           |
| Jadhav et al. (2022) [26] | -             | -        | -      | X           |

### 4. METHODOLOGY FOR LIFE CYCLE SUSTAINABILITY VALUE

The newly developed methodology involves the development of an integrative model based on QFD. Subsequently, Zhang's model [23] was modified and extended to include a social component and further adaptations. The methods consist of three different phases: (1) Determination of the sustainability requirements; (2) Matching and evaluation of solution concepts; (3) Solution transfer to QFD. The phases will be described in the following chapters.

#### 4.1 Phase 1: Definition of sustainability requirements

In the first phase, the requirements concerning sustainability are determined. For this purpose, different requirements are gathered via four different houses of quality (see Figure 3). For each house, the evaluation according to the rules and method of the HQ is being performed regarding a long-term life cycle impact perspective.

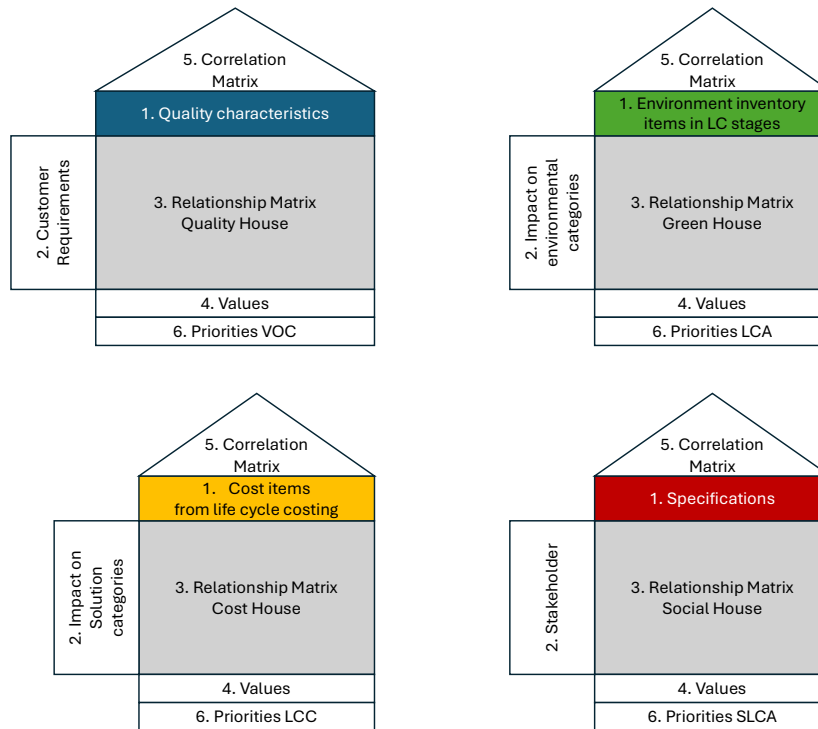


Fig. 3. Overview QFD models.

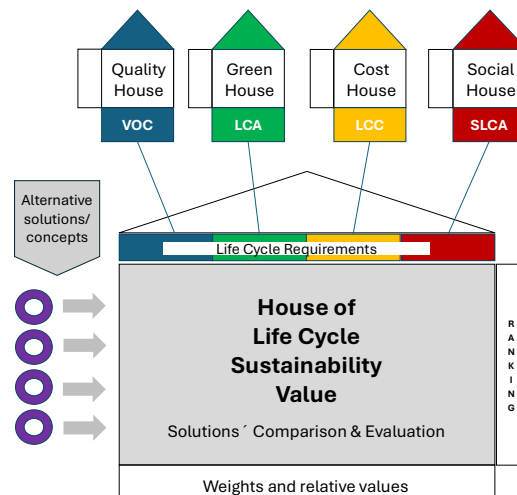


Fig. 4. Life Cycle Sustainability Value

Life Cycle Sustainability Value can be seen in Figure 4. The first house is the Quality House (QH). It contains the customer requirements, recorded by the Voice of Customer (VOC). Alternatively, the requirements consist of the “functional unit” or required “quantity structure” which potential solutions must fulfill. The second house, the Green House (GH) contains the environment inventory items from the life cycle assessment (LCA) and evaluates their impact on different environmental categories. The third house, the Cost House (CH), contains all cost items from the life cycle cost assessment (LCC) and evaluates how and if they affect certain categories (e.g., quality) positive or negative if costs are reduced. The fourth house, the Social House (SH), contains the desired social requirements that possible solutions must meet.

These criteria might be derived from various stakeholder groups such as workers (e.g., working conditions), society (e.g., labor safety and health), consumers (e.g. environmental friendliness), society (e.g., reverse logistics and disposal), supply chain (e.g. integrity of suppliers and sub-suppliers). In the social house, a social life cycle assessment (SLCA) is being performed to identify the important social criteria solutions have to meet.

## 4.2 Phase 2: Matching and evaluation of solution concepts

In the second phase, the core or most critical requirements derived from the four houses from phase 1 are matched with the (existing or to be developed) alternative solution concepts. For this purpose, a Concept Comparison House (CCH, see Figure 5) is being applied. As a result of this phase, the user gets a satisfaction factor for each solution alternative based on the critical requirements taken from the QH, GH, CH and SH. Its value reflects an overall comparison between the solution alternatives in terms of the fulfillment concerning the previously identified requirements from the houses.

## 4.3 Phase 3: Solution transfer to QFD

In the third and final phase, the new requirements for the solution with the highest satisfaction value, i.e. the best product concept,

are transferred to the following QFD process and considered throughout the entire planning process (see Figure 5).

## 4.4 Discussion of the model

In comparison to the classical HQ from the theory, a competition analysis is omitted, since this is not needed for the comparison of solution concepts. Furthermore, the relative fulfillment values of the specifications are normalized over the sum of all absolute fulfillment values, instead of using the maximum fulfillment value of a specification.

Zhang's approach [23] has been modified in the newly added Social House to include social aspects coming from different stakeholders. Through this the methods integrate more arguments and a wider view of the problem.

From a critical point of view, it can be stated that the newly developed model is rather unoptimized for new developments but better suited for further developments of existing products or product variants or the comparison of alternative solutions. This is due to the comparison of alternatives in the CCH.

Another critical point is the availability of data. For example, to make accurate cost predictions with lifecycle costing, large amounts of data and experience are needed. If this data is missing or inaccurate, wrong predictions can occur, which can also have a negative impact on the evaluation of alternative concepts (if the selection is based on wrong or inaccurate costs). Furthermore, the interpretation of a "sustainable" product/solution/concept is to be considered relatively broad. Sustainability is what is best for the environment from a social and environmental perspective. Models such as those developed in this thesis, among others, always seek a compromise to ensure economic viability in companies. In this sense, sustainable solutions cannot produce "true or absolute" sustainability.

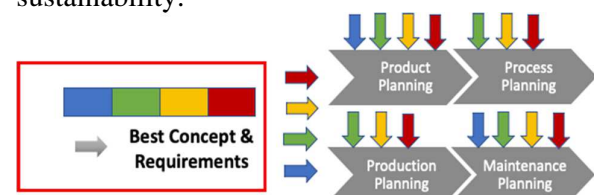


Fig. 5. Transfer of requirements into QFD.

The advantages lie especially in the structured recording of the parameters and the transparent calculation methodology. This creates a standardized basis for discussion for all stakeholders involved. As the points are awarded and the associated evaluation is carried out with the participation of all stakeholders, the acceptance of the result achieved increases. This saves time in determining the results. However, the central pivotal point is the determination of the respective weighting factors, which always gives rise to lengthy discussions. In the best-case scenario, agreement must be reached on this in advance. Depending on the stakeholder's wishes, the weighting of the three sustainability pillars - ecological, environmental and social - can be determined so that the best possible solution can be found among the assumed weighting factors.

## 5. CONCLUSION AND OUTLOOK

The integrative model of “Life Cycle Sustainability Value” developed in this work allows for a comprehensive evaluation of new solutions, products or product variants based on ecological, economic, and social aspects over the entire life cycle in one methodical approach. The resulting new approach considers all three pillars merged into one model, called “the life cycle sustainability value”. The model considers, analogously to the House of Quality, in a Quality House, Green House, Cost House and Social House, on the one hand customer demands with the Voice of the Customer, but also the three sustainability goals for a new product and converts all requirements in a Concept Comparison House into a “satisfaction value” for alternative solutions, product or production concepts.

The presented approach ensures that sustainability requirements are directly integrated into the development process in a structured manner. The comparison of different product alternatives is also facilitated, providing valuable insights for decision-making. The integrative method of “Life Cycle Sustainability Value” (LCSV) provides a valuable tool for evaluating the sustainability of alternative solutions, new products or product variants. By incorporating ecological, economic, and social aspects into the Quality Function Deployment

process, companies can better meet the growing demands and requirements of sustainability while also fulfilling their economic interests and goals.

Future research will focus on the direction related to the trends associated with the LCSV method in action (as suggested by the [29-30]):

1. Increased focus on adopting circular economy practices - This involves implementing practices and methodologies related to design for sustainability, reuse, and recycling, as well as implementing systems for recovering and repurposing materials at the end of their life;
2. Growing demand for transparency and traceability - This is driving demand for greater traceability and transparency throughout the supply chain;
3. Integration of emergent digital technologies like blockchain, IoT, and AI which have been started to be used for improving the efficiency and accuracy of LCSV assessments;
4. Expanding scope of LCSV assessments to include social and economic impacts as well. This broader perspective recognizes that sustainability is a complex issue that requires consideration of all three dimensions;
5. Development of standardized methodologies - This will help to ensure the consistency of the assessments and that the results are comparable across different products and companies;
6. Increased collaboration and partnerships which means to enhance collaboration and partnerships among different stakeholders, including businesses, governments, NGOs, and research institutions. Thus, the formation of new alliances and initiatives focused on promoting LCSV could be established.

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### O metodă de evaluarea valorii sustenabilității ciclului de viață a soluțiilor alternative de proiectare

Lucrarea se concentrează pe dezvoltarea unei metodologii integrative de evaluare a sustenabilității ecologice, economice și sociale a opțiunilor de proiectare a soluțiilor alternative. Abordarea de bază constă în extinderea metodei clasice de implementare a funcției calității (QFD) către un model holistic integrat pentru evaluarea generală a diferitelor aspecte ale celor trei piloni ai durabilității pe parcursul ciclului de viață al produsului. Metodele identifică aspectele-cheie și permit utilizatorilor să ia în considerare și să pondereze diferite aspecte ale ciclului de viață într-o schemă globală de notare.

**Cuvinte cheie:** Evaluarea ciclului de viață (LCE), Casa Calității (HQ), Implementarea funcției de calitate (QFD), sustenabilitate.

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