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BILECIK SEYH EDEBALI UNIVERSITY

INSTITUTE OF GRADUATE EDUCATION

DEPARTMENT OF INDUSTRIAL SUSTAINABILITY

EXAMPLE APPLICATION IN SUSTAINABLE INDUSTRIAL PRODUCT DESIGN: 22 kW AC ELECTRIC VEHICLE CHARGING STATION

MASTER’S THESIS

MUSTAFA CANBULAT

SUPERVISOR

PROF. DR. AHMET FEVZİ SAVAŞ

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DECLARATION

I hereby declare that, during the preparation and writing of my master's thesis titled "Example Application in Sustainable Industrial Product Design: 22 kW AC Electric Vehicle Charging Station," I have adhered to the principles of scientific research and ethics; that I have properly cited all sources from which I have benefited, in accordance with scientific standards; that I have not falsified any of the data used; that no part of this thesis has been submitted as another thesis work at Bilecik Seyh Edebali University or any other university; that I accept all legal responsibilities that may arise in the event that the contrary is found; and that the information I have provided is accurate.

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PREFACE

I would like to express my heartfelt gratitude to my esteemed advisor, Prof. Dr. Ahmet Fevzi SAVAŞ, who guided me with his academic knowledge, industry experience, and life experience throughout my bachelor’s, master's, and thesis studies; to my esteemed professor, Assoc. Prof. Dr. Şenay BALBAY, who broadened my vision with her valuable knowledge and work in the field of Industrial Sustainability; to my esteemed professor, Assoc. Prof. Dr. Nazife Aslı KAYA ÜÇOK, who guided my education in Industrial Design and my professional life with her technical and philosophical insights; and to my esteemed teacher, Ms. Lendagül AYHAN CENGİZ, who was not only my high school advisor but also showed me that life is an education and has always been my teacher on this journey.

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ABSTRACT

EXAMPLE APPLICATION IN SUSTAINABLE INDUSTRIAL PRODUCT DESIGN: 22 kW AC ELECTRIC VEHICLE CHARGING STATION

The carbon emissions brought about by industrialization are increasing globally with each passing day. This rise is triggering the climate crisis, causing unexpected natural events, and making the concept of sustainability even more important. However, sustainability has not yet fully developed across different disciplines and sectors. In this study, sustainable design strategies have been investigated and applied in industrial design.

The study aimed to produce applicable results for both science and industry through university-industry collaboration. Strategies related to sustainable design were investigated under the following headings: EU Ecodesign, Cradle to Cradle (C2C) Design, Life Cycle Assessment (LCA), Eco Label, CE Certification, and Circular Economy. The strategies were evaluated in terms of their impact and scope, and the most effective sustainable design strategy for the product's target market was determined. Within the framework of industry collaboration, the target market for the planned 22 kW AC electric vehicle charging station was identified as Germany, and it was found that the EU Ecodesign strategy was the most suitable. Furthermore, to create a comprehensive application of industrial product design processes, the following steps were taken: Concept designs were developed using the Design Thinking methodology, a concept was selected by the industrial partner using the Quality Function Deployment (QFD) methodology, material combinations were created through the Rule of Mixture methodology, and finally, static stress analyses were performed on the parts whose engineering design had been completed. The most suitable material combination was then determined based on the safety factor values.

Upon completion of the industrial product design processes, a scaled model was created, and assembly was carried out using the electronic components provided by the company. In this way, it was practically demonstrated that determining and applying the correct sustainable design strategy in terms of impact and scope can reduce carbon emissions by 25% during the product design process alone. The raw material emissions for the parts designed in industrial design amounted to 8.848 kg of CO_2.

Keywords: Industrial Design, Sustainable Design, Ecodesign, Electric Vehicle Charging Station, Carbon Emission

ÖZET

SÜRDÜRÜLEBİLİR ENDÜSTRİYEL ÜRÜN TASARIMINDA ÖRNEK UYGULAMA: 22 kW AC ELEKTRİKLİ ARAÇ ŞARJ İSTASYONU

Endüstrileşmenin beraberinde getirdiği karbon emisyonları global ölçekte her geçen gün artmaktadır. Bu artış ile birlikte iklim krizi tetiklenmekte, beklenmeyen doğa olayları oluşmakta ve sürdürülebilirlik kavramı daha da önem kazanmaktadır. Ancak sürdürülebilirlik, farklı disiplinlerde farklı sektörlerde henüz gelişimini tamamlamamıştır. Söz konusu çalışma ise sürdürülebilir tasarım stratejilerinin araştırıldığı, endüstriyel tasarımda uygulandığı bir çalışma olmuştur.

Çalışma kapsamında üniversite ve sanayi iş birliği yapılarak bilim ve endüstri açısından uygulanabilir sonuçlar doğurmak hedeflenmiştir. İlk olarak sürdürülebilir tasarımla ilişkili stratejiler; AB Ecodesign, Beşikten Beşiğe (C2C) Tasarım, Yaşam Döngüsü Değerlendirmesi (LCA), Eco Label, CE Sertifikasyonu, Döngüsel Ekonomi başlıkları altında araştırılmıştır. Buna istinaden stratejilerin etki ve kapsam bakımından değerlendirmeleri gerçekleştirilerek ürünün hedef pazarına yönelik en etkin sürdürülebilir tasarım stratejisi belirlenmiştir. Sanayi iş birliği çerçevesinde tasarımı planlanmış 22 kW AC elektrikli araç şarj istasyonu için hedef pazar Almanya olarak belirlendiğinden AB Eko Tasarım stratejisinin en uygun strateji olduğu görülmüştür. Bununla birlikte endüstriyel ürün tasarım süreçlerinin kapsamlı bir uygulama oluşturması için sırasıyla; design thinking (tasarım odaklı düşünme) metodolojisi uygulanarak konsept tasarımlar geliştirilmiş, kalite evi metodolojisi uygulanarak sanayi iş birliği yapılan şirket tarafından konseptler puanlanmış, malzeme seçimleri kapsamında karışım kuralı metodolojisi uygulanarak karışımlar oluşturulmuş ve ardından mühendislik tasarımı tamamlanan parçalara statik stres analizleri uygulanarak güvenlik faktörü değerleri üzerinden en uygun malzeme karışımı belirlenmiştir.

Endüstriyel ürün tasarımı süreçlerinin tamamlanması ile birlikte ölçekli model oluşturularak şirket tarafından sağlanan elektronik parçalarla montaj gerçekleştirilmiştir. Doğru sürdürülebilir tasarım stratejisi belirlemenin ve uygulamanın sadece ürün tasarımı sürecinde %25 oranında karbon emisyonu düşürebildiği uygulamalı olarak görülmüştür. Endüstriyel tasarım kapsamında tasarlanan parçaların ham madde emisyonu 8.848 kg CO_2 olmuştur.

Anahtar Kelimeler: Endüstriyel Tasarım, Sürdürülebilir Tasarım, Eko Tasarım, Elektrikli Araç Şarj İstasyonu, Karbon Emisyonu

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LIST OF ABBREVIATIONS AND SYMBOLS

GHG: Greenhouse Gas Emissions

CBAM: Carbon Border Adjustment Mechanism

SPD: Sustainable Product Design

EU: European Union

C2C: Cradle to Cradle

LCA: Life Cycle Assessment

HoQ: House of Quality

RoM: Rule of Mixture

SF: Safety Factor

CAE: Computer Aided Engineering

GD: Green Deal

PET: Polyethylene Terephthalate

CE: Conformité Européenne

ISO: International Organization for Standardization

GEN: Global Eco Labelling Network

EMC: Electromagnetic Compatibility

EV: Electric Vehicle

AC: Alternating Current

DC: Direct Current

1. INTRODUCTION

This study, within the scope of Industrial Sustainability and Industrial Design, focuses on how to develop a product that can address today's sustainability and industrial challenges. The concept of sustainability has emerged as a consequence of the linear economy, which is increasingly shaped by mechanization and mass production (Herrmann et al., 2014). This consequence leads to resource depletion, a decrease in economic stakeholders, and an acceleration of sectoral changes in industry due to dwindling resources. The concept of the circular economy has gained importance precisely within this framework and has taken its place in the literature (Sariatli, 2017). As a result of the destructive impact of unlimited industrial production on nature and resources, the effects of climate change and global warming have begun to increase (Dietz et al., 2020). These increases lead to unpredictable natural events and unsustainable resource management every year. This situation increases economic burdens, causing the industry and supply chain to constantly change, resulting in various damages. All of these can be attributed to the linear economic model, and the increase in mass production also brings with it the problem of a growing population (Herrmann et al., 2014). It is observed that the sectors that cause the most damage to nature are actually the sectors with the most dependence, namely energy production, transportation, and industry. This situation is also evident in the distributions presented in Figure 1.1.

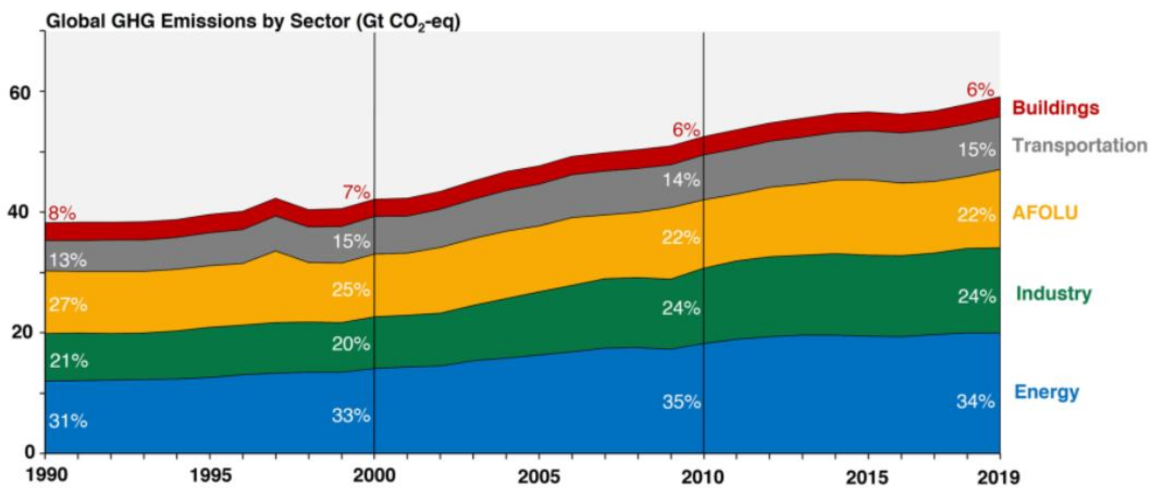


Figure 1.1. Change in Greenhouse Gas Emissions by Economic Sector Over the Years

Source: (United States Environmental Protection Agency)

In the visual presented in Figure 1.1, the emissions from buildings are represented in red, emissions from transportation are represented in gray, emissions from agriculture, forestry, and other land uses are represented in yellow, emissions from industry are represented in green, and emissions from the energy sector, in terms of Gt CO2 and equivalent gases, are represented in blue, showing the changes over the years. In response to this situation, Industrial Sustainability has become one of today's trending scientific disciplines. It emerges as a field of study that encompasses minimizing the environmental impact of industrial processes, conserving resources, and managing design and production processes in a way that enhances social and economic well-being (Ny et al., 2005: 99). It covers a wide range of strategies, including energy efficiency, waste reduction, resource conservation, and the use of sustainable materials (Graedel and Allenby, 2003). A critical aspect of this discipline is the calculation and reduction of emissions, especially greenhouse gases (GHGs), which exacerbate the effects of climate change. Emission calculations involve assessing the carbon footprint of industrial activities, from raw material extraction to product disposal, and implementing measures to reduce these emissions.

The European Union has reached significant agreements in the fields of development and trade within the framework it calls the Green Deal. According to this agreement, also known as the European Green Deal, the aim is for the European Union to become a modern and highly resource-efficient place. It has important goals such as achieving net-zero emissions by 2050 and growth independent of resource use (European Commission, 2020). Today, to implement these goals and to prevent companies producing goods imported into the European Union from gaining an unfair advantage over companies operating within its borders, which will make investments and incur financial burdens to reduce carbon emissions, the EU has established the Carbon Border Adjustment Mechanism (CBAM) (Teevan et al., 2021). This mechanism will ensure similar conditions for all companies engaged in commercial activities with the European Union. Under CBAM, companies' emissions will be evaluated on a Scope 1 and Scope 2 basis, and Scope 3 has not yet been included due to the system's novelty (Clora et al., 2023). Thus, carbon taxation will be applied based on the calculated emission values, with the aim of reducing emissions by ensuring that those causing high emissions pay higher taxes. The Scope 1, 2, and 3 values mentioned here define the frameworks for emission calculations. Scope 1 covers emissions directly caused and controlled by the organization; Scope 2 covers emissions indirectly caused by the organization and emissions from purchased sources (such as natural gas and electricity); and Scope 3 encompasses emissions not produced by the organization itself, but by stakeholders and companies in the supply chain, and all emissions not included in Scope 1 and 2 (National

Grid, 2024). This situation, in fact, contributes to the development of concepts such as sustainability, circular economy, sustainable product design, and greenhouse gas emission calculations, as it brings with it legal obligations for the application of these concepts.

Sustainable industrial practices are guided by frameworks such as the circular economy and sustainable product design (SPD). The circular economy aims to create closed-loop systems where resources are continuously returned to the economy and production processes, waste is minimized, and resource efficiency is promoted (Ellen MacArthur Foundation, 2015). SPD aims to integrate environmental, social, and economic considerations into the product development process, designing products for durability, recyclability, and minimal environmental impact (Bhamra and Lofthouse, 2007).

Industrial Design is a discipline focused on designing and developing products that are competitive in terms of both functionality and aesthetics. It can be said that it is involved in the design processes of all products that utilize industrial production techniques. It involves a multidisciplinary approach that combines art, engineering, and business to design products that meet user needs and market demands (Canbulat and Savaş, 2024). Industrial designers must consider various factors such as ergonomics, usability, materials, manufacturing processes, and sustainability in today's market and industrial conditions to create innovative, efficient, and user-friendly products (Ulrich and Eppinger, 2016). The role of industrial design in promoting sustainability is increasingly recognized. By incorporating sustainable design principles, industrial designers have the potential to create products that minimize environmental impact, enhance resource efficiency, and promote social well-being. This includes selecting sustainable materials, designing for durability and repairability, and planning for the entire life cycle of the product under these conditions (Berberoğlu, 2024).

The aim of this study was to investigate sustainable design strategies, conduct a case study, and provide guidance to both local and global industries through this application. Within the scope of this study, design strategies introduced by the global market in relation to the concept of sustainability were researched, and a sustainable design case study will be carried out in collaboration with industry, focusing on an alternating current (AC) electric vehicle charging station, which is part of the transition to electric vehicles for the purpose of reducing emissions (Wang et al., 2021). Today, under the concept of sustainability, the transition to electric vehicles has accelerated due to the aim of avoiding fossil fuel use (Sanguesa et al., 2021). The design and production of electric vehicle charging stations have gained momentum in this process. These products are manufactured to charge electric vehicles using AC and DC (direct current), with charging times being much shorter with DC products than with AC products (Savari et al., 2023). When considering cost and mass, AC products are found to be much lighter and suitable for home use, while DC products are connected to the power grid, operate at high voltage, and perform charging at different speeds depending on their capacity (Savari et al., 2023). However, while the shift away from fossil fuels and the transition to electric vehicle technology are observed under the umbrella of sustainability, it is also observed that electric vehicles are being mass-produced from scratch, creating a demand in the market equal to the number of existing vehicles instead of recycling them, and the design and production of electric vehicle charging stations are accelerating to meet this demand. Under these conditions, the need to understand how to design sustainable products for the global industry is gaining importance, and the gap in the literature in Türkiye regarding what sustainable design strategies are makes this study significant. In this context, the aim was to conduct comprehensive literature reviews on sustainable design strategies to determine the most appropriate design strategy or strategies and to carry out product design in collaboration with an R&D company through industry-university cooperation. Within the scope of this study, literature review activities were conducted under the headings of EU Ecodesign Directives, Cradle to Cradle (C2C), Life Cycle Assessment (LCA), Eco Label, sustainability in CE (Conformité Européenne) certification, and Circular Economy.

The strategies identified in the literature review presented in Chapter 2 were examined in detail in terms of scope, impact, and suitability. Based on the objectives of the industrial collaboration, the appropriate design strategy was followed within the framework of scope and impact. Chapter 3 outlines the methodologies to be used and their details, which are: design strategy, design thinking, House of Quality (HoQ), Rule of Mixtures (RoM), safety factor, and emission calculations based on mass and geometric data. Chapter 4 presents the results of using various methodologies, including product concept designs developed within the framework of the design strategy using the design thinking methodology, House of Quality (HoQ) for concept evaluation, Rule of Mixtures (RoM) for material selection, and Computer-Aided Engineering (CAE) for safety factor (SF) analysis.

Concept designs will be developed using design thinking to understand user needs, generate innovative ideas, and incorporate features mandated by the concept of sustainability (Arifin and Mahmud, 2021). Along with the concept design, the House of Quality methodology will be applied, with scoring performed by company representatives within the industrial collaboration, leading to the selection of a final concept (Francis, 2016). The Rule of Mixtures will guide the selection of sustainable materials, ensuring that the chosen materials meet performance and environmental criteria (Chawla and Chawla, 2013). Safety factor (SF) analysis in Computer-Aided Engineering will ensure the structural integrity of the design and product reliability corresponding to the material selection (Hutton, 2004). By implementing all these steps, answers to the following questions will be sought:

1. How should sustainable design be implemented?
2. How should optimal material selection be performed in terms of emissions in design?
3. Can control over product emission values be achieved through sustainable design?
4. Is sustainable design, as its name suggests, sustainable, and does it benefit nature?
5. How does the implementation of sustainable design in the product design process affect the manufacturer's economic situation?

Thus, a case study of sustainable product design will be carried out, aiming to create guiding results for academia and industry in sustainable product design.

2. LITERATURE REVIEW

Sustainable design has become a critical focus in product development due to increasing environmental concerns and regulatory pressures. Within this framework, this literature review focuses on six key sustainable design strategies, considering both policy and global awareness and applicability. These are: the EU Ecodesign Directive (Ecodesign), Cradle to Cradle (C2C) Design, Life Cycle Assessment (LCA), Sustainable Product Design (SPD), and the Circular Economy (Peralta et al., 2021). Sustainable Product Design was examined under two headings: Eco Label and Sustainability in CE Certification. Each strategy offers different approaches and methodologies to minimize environmental impact and promote sustainability in product design. Each strategy was examined as part of the literature review, and the specific scopes of the strategies for wood and thermoplastic products were investigated in detail, given the target product of this study.

2.1. EU Ecodesign Directive

The Ecodesign Directive (Directive 2009/125/EC), replacing the previous Directive 2005/32/EC, is a directive adopted by the European Parliament and the Council in 2009. The main objective of the Directive is to establish a framework for setting mandatory ecological requirements for energy-using and energy-related products. These requirements aim to improve the overall environmental performance of products by taking into account factors such as energy consumption, resource efficiency, and waste generation (European Commission, 2009). The Directive is part of the EU's strategy to promote sustainable development and reduce greenhouse gas (GHG) emissions. It is aligned with other EU policies, such as the Circular Economy Action Plan and the European Green Deal (GD), which aim to transform Europe into a more sustainable and circular economy (European Commission, 2020).

The Ecodesign Directive provides a framework for the development of implementing measures that establish sustainability requirements for different product categories. These measures are developed through a process that includes extensive stakeholder consultations, impact assessments, and scientific research. These requirements cover various aspects of product design, such as energy efficiency, material use, recyclability, and the presence of hazardous substances (Dalhammer et al., 2014). For example, while increasing the energy efficiency of a product, the use of materials that are difficult to recycle or dispose of safely should be avoided. One of the most prominent features of the Directive is its "cradle-to-grave" approach, which considers the environmental impacts of products throughout their entire life cycle. This approach prevents improvements made in one stage of the product's life cycle from leading to negative consequences in other stages (Siemens, 2023). For example, changes made to increase a product's energy efficiency should not lead to the use of materials that are difficult to recycle or dispose of safely. The EU Ecodesign Directive has had a very significant impact on production and design activities within the European Union, and this impact is increasingly spreading worldwide due to the mandatory requirements for companies wishing to export to and import from the European market. According to research, this strategy has led to a decrease in emissions, an increase in the impact of recycling in product design strategies, and a decrease in the linear economy approach. Therefore, in 2022, a new proposal was made for the EU Ecodesign Directive, and work has begun to extend its application beyond products that operate with electrical energy and can provide efficiency, to all products in the internal market (Heinemann and Arsenio, 2022).

In this design directive, wood and thermoplastic materials are widely used in product development, with examples in furniture, automotive, and consumer electronics. Due to the requirements of the Directive, factors such as material selection, design for recyclability, and product environmental performance are prominent in these designs. For example, products made with thermoplastic materials are found in many different sectors, and there is a significant need in each sector. However, the environmental impact of thermoplastic materials increases significantly if waste management is not carried out properly or if cradle-to-grave processes are not implemented sustainably, causing serious damage to the environment. At this point, the Ecodesign Directive has made it mandatory to specifically plan the production-to-disposal processes for products to be designed sustainably, aiming to increase recyclability and reduce environmental damage (Fenwick et al., 2023). One of the most important factors encouraging manufacturers to use thermoplastics is their ease of production and recyclability at the end of the product life cycle. However, the need to comply with the Ecodesign Directives has led to the requirement of mixing fewer different types of thermoplastic materials and avoiding additives in thermoplastic material selection. In addition, these directives have guided material selection in the market by prioritizing the use of biodegradable and natural plastics in thermoplastic material use (Bos et al., 2024). However, research shows that recycling thermoplastics is not an infinite process, and with each recycling cycle, the durability of the product decreases compared to the previous one (Gadhave et al., 2022). Therefore, the recycling stages of thermoplastics are also a finite cycle. The emissions per product can be reduced by increasing the number of reuses.

Besides thermoplastic materials, one of the most important recyclable materials is wood. This type of material has also been subject to more sustainable use within the framework of the Ecodesign Directives. Since wood is a natural material, it has a much lower carbon footprint than other materials. However, the sustainability of wood materials varies depending on the type of wood and the chemicals used on it. In this context, the Ecodesign Directive prioritizes the use of recyclable wood and reinforces the reduction of harmful chemical use on wood (Swedish Forest Industries Federation, 2024). One of the key aspects of sustainability in wood use is the management of the forest where the wood is produced and the production emissions in this process. There are various global certifications (PEFC, FSC) in this context, such as certifications that ensure that wood is produced with minimal harm to nature and that the wood obtained from the forest does not harm the ecological balance (Mikulková et al., 2015). In addition, the EU Ecodesign Directive also prioritizes repairability, durability, and long-term use in products made using wood. This situation encourages the use of high-quality materials and the production of products that will be used for a long time. Designing wooden parts to be easily disassembled is also a parameter that increases recycling and reduces waste generation (Bovea and Pérez-Belis, 2012).

According to research, the Ecodesign Directive is a regulation developed to improve the environmental performance of products. The Directive promotes the recycling of parts or entire products made of thermoplastic and wood materials, the use of materials from natural sources, design for disassembly/replaceability, and the reduction of harmful chemicals. In addition to all this, it emphasizes long-term and durable use. However, there are challenges in implementing the Directive, particularly in balancing environmental performance with other factors such as cost, functionality, and consumer preferences. Additionally, the rapid pace of technological advancements and changing market dynamics require continuous updates to the implementing measures to ensure their relevance and effectiveness. Nevertheless, the Ecodesign approach, spreading globally through companies within the European Union and those exporting products to this region, is of critical importance in reducing global emissions through commercial necessity (Staniszewska et al., 2020).

2.2. Cradle to Cradle (C2C) Strategy

The sustainable design strategy known as Cradle to Cradle (C2C) was introduced by architect William McDonough and chemist Michael Braungart in their book "Cradle to Cradle: Remaking the Way We Make Things" (McDonough and Braungart, 2002). With the Cradle to Cradle Products Innovation Institute, which they founded in 2012, they have become a global product certification body that directly influences the sustainability of products in this field. Starting with their own circles and becoming recognized by various organizations, the certifications they provide are accepted by various institutions and organizations, primarily in Europe and America. In this strategy, the sustainable aspects of products are addressed in five categories. These are: material health, product circularity, clean air & climate protection, water & soil stewardship, and social fairness (Cradle to Cradle Products Innovation Institute, 2024).

Under the material health category in the Cradle to Cradle (C2C) strategy, the chemicals used in the production of the material are examined. These chemicals must not be harmful to human health or the environment. In addition, long-term use durability and recyclability are important under this heading. The product circularity category involves designing products to be intentionally repurposed after use, including how they will be used after transformation. Under the clean air & climate protection category, it is important that the product does not harm air quality during production, does not increase greenhouse gases that trigger climate change, and promotes the use of renewable energy. The water & soil stewardship category aims to protect water and soil ecosystems. The focus here is on access to clean and safe water and soil for all living things. It is expected not to harm the ecology. Under the social fairness category, companies are expected to value their human resources in an equal, fair, and equitable manner. The C2C design strategy has become a strategy that reduces negative environmental impacts by focusing on these areas, ensuring the use of safe and recyclable materials, and promoting the use of renewable energy. Research shows that using the C2C strategy can enable companies to achieve economic benefits by continuously recycling their products, and contribute to the creation of new business opportunities, allowing companies to continue their activities sustainably (Charter and Tischner, 2001). From the designers' perspective, it is believed that using the C2C strategy encourages designers to think differently and positively affects the creation of more unique and creative products (Bakker et al., 2010). There are various positive and negative aspects to implementing the C2C strategy. It has a certification that has gained trust due to its long-standing activity in the global market. The certification process focuses not only on environmental impacts but also on social impacts, which leads to extra costs. It is a preferred certification due to its international nature (Minkov et al., 2018).

As well as focusing on the strategies in the literature, this study also specifically investigates how these strategies are applied to wood and thermoplastic materials. Within this framework, it is understood that in the C2C design strategy, the choice of natural, biodegradable thermoplastics or products that can be recycled in terms of product circularity should be prioritized over industry-standard thermoplastics. Examples include redesigning the product for the use of recycled (performance-degraded) thermoplastics, and creating PET bottles from PET material recycled from PET packaging (Hopewell et al., 2009). For minimal environmental impact in wood material use, parameters such as the source of the forest (soil ecology is specifically addressed as a category in this strategy), the chemical substances in the wood within the scope of material health, and what will be done with the product at the end of its life cycle after use are examined. At this point, similar to the Ecodesign Directive, forest management is again a key point and requires PEFC and FSC certifications. In general, this strategy is a strategy and certification that has been institutionalized through the efforts of individuals, starting in their own circles and spreading, and has begun to be accepted in almost all countries, especially in Europe and America. It is detailed in five sub-categories based on the key headings of material selection and product circularity. While its global market acceptance is weaker from a political perspective compared to the EU Ecodesign, another strategy, it can be seen that it is an extremely positive strategy in terms of environmental impacts, sustainability, and business organizations.

2.3. Life Cycle Assessment (LCA) Strategy

Life Cycle Assessment (LCA) is a sustainability strategy that came into effect under the ISO 14040 standard by ISO in 2006. This strategy addresses the subject under four headings. These are: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO, 2006). Defining these headings as phases, the goal and scope definition phase involves defining the purpose of the LCA study, the system boundaries, and the functional unit. The functional unit is a measure of the function of the system under study and provides a reference unit for understanding inputs and outputs (Guinée, 2004). In the inventory analysis phase, the relevant inputs and outputs of the system are compiled. This involves data related to energy and material flows, emissions, and waste associated with each stage of the product life cycle (Demirer, 2011). In the impact assessment phase, the data obtained from the previous phase are converted into potential environmental impacts. These impacts must be categorized and measured, such as global warming potential, acidification potential, and resource depletion. In the final phase, interpretation, results and recommendations are presented. Rational analysis of the results, identification of environmental impacts, assessment of data quality, and evaluation of the rationality of the results are carried out in this phase. Key points in the LCA strategy can be considered as market trends and consumer behavior (Bergerson et al., 2020).

The LCA strategy provides a holistic view of a product's environmental impacts, helping designers and decision-makers identify opportunities for improvement and make informed choices. However, there are both advantages and limitations to implementing LCA. Looking at the advantages, it offers a comprehensive analysis of a product's environmental impacts throughout its entire life cycle. Unlike other strategies, finding and improving various environmental problems in this context is crucial for reducing greenhouse gas emissions and environmental damage at the company level (Manzardo et al., 2018). In this framework, a clear understanding of environmental impacts paves the way for conscious and effective decisions in product design, production policies, and material selection (Spreafico, 2022). It is believed that industrial organizations that implement the LCA strategy will be able to easily comply with standards that may be introduced as restrictions in the global market (such as the EU Ecodesign Directive). In particular, the rational evaluations within the scope of investigating environmental impacts positively affect this strategy. When considering the limitations, detailed data collection on material and energy flows, emissions, and waste is an intensive and costly process. The complexity of the methodology is a limiting factor for SMEs in terms of manpower and resources. LCA results can undergo radical changes due to variations in fixed coefficients obtained from other institutions or organizations. For example, if coefficients obtained from institutions, such as the electricity emission coefficient, change, all LCA results will also change, which is a negative parameter for the process. It is very difficult to derive or understand social impacts from this strategy (Jørgensen et al., 2008). This also constitutes a negative parameter for the strategy in question.

Similar to previous strategies, in this strategy, for thermoplastic or wood products to be sustainable, topics such as forest management and not harming the ecology are included for wood products, while for thermoplastic materials, the importance of being made of materials that are less harmful to nature, have a lower carbon footprint, and are harmless to environmental health comes to the fore. In summary, LCA emerges as a robust and comprehensive methodology for evaluating the environmental impacts of products throughout their life cycles. This strategy can help identify opportunities for improvement in material selection, processing, and end-of-life management for products with thermoplastic and wood components. LCA is a comprehensive strategy that supports informed decision-making in product design and production by providing a clear understanding of environmental impacts.

It promotes sustainable design and enables steps to be taken that positively support ecology as a global market effect. The reduction of emissions by organizations positively affects nature.

2.4. Eco Label Strategy

A key component of sustainable design is the implementation of Eco Label strategies. An Eco Label is a type of certification that guides consumers towards environmentally friendly products, encourages manufacturers to adopt sustainable practices, and promotes market-driven environmental improvements (Delmas and Grant, 2014). Eco Labels are certifications awarded to products that meet specific environmental performance criteria. These criteria typically address various stages of a product's life cycle, including raw material extraction, manufacturing, use, and disposal. The main purpose of an Eco Label is to provide consumers with clear and reliable information about the environmental impacts of products, enabling them to make informed purchasing decisions (Scheer and Rubik, 2005: 51).

Today, Eco Labels are issued under different names by many institutions and organizations. The fact that they are all called "Eco Label" leads to some confusion. The Global Ecolabelling Network (GEN), a non-profit international association of third-party environmental performance labeling organizations, includes members who operate some of the world's leading eco-labels, such as the EU Ecolabel and the Nordic Swan. In the European Union, it appears as a label given to products that meet certain restrictions throughout their life cycles (European Commission, 2024). The Blue Angel, recognized by the German Federal Environment Agency, is a well-established Eco Label approach in Germany (Blauer Engel, 2024). In this context, it is seen that the definition of Eco Label is very broad, with various accreditations and frameworks operating under the same name, used by different countries and organizations to perform Eco Label certification.

According to ISO standards, Eco Label Type I appears as ISO 14024. This standard specifies principles and procedures for the development of Type I environmental labeling programs, including the selection of product categories, product environmental criteria, and product functional characteristics (ISO, 2018). Type II, under ISO 14021, provides guidance on terminology, symbols, and testing and verification methodologies for self-declared environmental claims (ISO, 2016). Type III, defined under ISO 14025, specifies principles and procedures for the development of Type III environmental declarations, including the use of Life Cycle Assessment and environmental performance data (ISO, 2006). The common requirements agreed upon by many organizations for obtaining an Eco Label are LCA, resource use for the production of products and emissions resulting from these uses, independent third-party assessment, and public disclosure of data. Thanks to these requirements, both manufacturers and Eco Label certification bodies can make their declarations publicly.

While Eco Labels offer numerous benefits, some challenges persist. These include the proliferation of labels, which causes consumer confusion, and the cost and complexity of certification for manufacturers. Overcoming these challenges requires continuous improvement in label standards, increased collaboration among stakeholders, and strong monitoring and enforcement mechanisms. Despite these challenges, eco-labels offer significant opportunities for advancing sustainable design. They can encourage innovation by incentivizing manufacturers to develop environmentally friendly products, increase market differentiation, and build consumer trust (Frankl et al., 2005). As demand for sustainable products increases, Eco Labels are playing an increasingly vital role in guiding both consumers and manufacturers towards more sustainable choices.

2.5. Sustainability Strategy in CE Certification

The CE marking, a symbol indicating a product's conformity with European Union legislation, is crucial for sustainable design, ensuring that products meet environmental and safety standards (European Commission, 2021). CE, an abbreviation of "Conformité Européenne," signifies that the product conforms to European regulations (International Trade Administration, 2022). This ensures the free movement of products bearing this mark within the European Economic Area. The CE marking itself is not a sustainability certificate. However, it encompasses directives that include environmental considerations and contribute to the overall goals of sustainable design (Milovanović et al., 2011). In this context, the role of CE certification in sustainable design is also of significant importance. CE certification encourages manufacturers to comply with sustainability principles, such as reducing environmental impact and ensuring resource efficiency. The CE marking is required for a wide range of products, including electronics, machinery, and construction materials, all of which can significantly benefit from sustainable design practices.

To obtain CE certification, the applicable directives must first be determined, followed by an assessment of product requirements. After this step, product conformity assessment and technical documentation must be carried out, respectively. Finally, the CE marking must be affixed to the product, and conformity must be maintained (Năsulea and Năsulea, 2019). Examining these steps in more detail, "applicable directives" refers to determining which directives are relevant to the product. Depending on the product type, this may include the

Low Voltage Directive (LVD), the Electromagnetic Compatibility (EMC) Directive, the Restriction of Hazardous Substances (RoHS) Directive, and the Ecodesign Directive (Hanson, 2005). The "assessment of product requirements" refers to the specific directives that must be met for each product. For example, when it comes to energy efficiency, material use, or environmental impacts, compliance with EU Ecodesign 2009/125/EC is required (European Commission, 2009). "Conformity assessment" includes the manufacturer's internal production control, quality assessment, and tests to be carried out by third parties. "Technical documentation" refers to documents that clearly express the product's compliance with the relevant directives. The documents in this documentation include design and manufacturing details, risk assessments, and test reports. After all these requirements, the CE mark can be affixed to the product (Năsulea and Năsulea, 2019).

The restriction of hazardous substances is one of the most prominent examples of the relationship between CE marking and sustainability (Chancerel, 2010). In addition, there are many directives for CE certification, and these vary depending on the product group. However, the directives that commonly apply to many products are the Low Voltage Directive (2014/35/EU), the Electromagnetic Compatibility Directive (2014/30/EU), the Machinery Directive (2006/42/EC), the Restriction of Hazardous Substances Directive (2011/65/EU), and the Ecodesign Directive (2009/125/EC) (Hanson, 2005).

According to information from the European Commission, an important point about CE marking is made. It is specifically stated that products bearing the CE marking cannot be considered as safe products approved by the EU or any other authority, nor does it provide information about the origin of the product (European Commission, 2021).

2.6. Circular Economy Strategy

The concept of the circular economy is a sustainable strategy that has emerged with the increase in the unsustainable consequences of the linear (take-make-dispose) economic model. The aim of the circular economy is to avoid depleting resources, to prevent unpredictable consequences by harming the environment, and to ensure that the workflow continues in a sustainable and repeatable manner so that the work done can be continued (Ellen MacArthur Foundation, 2015). Since the goal of the linear economic model is relentless growth and making more money, resource depletion and the unsustainable consequences of the process have been influential in the emergence of such sustainable strategies (Sariatli, 2017).

There are several key points in the circular economy. Designing products and processes that minimize pollution through the use of materials and processes that reduce environmental impact, and ensuring that products and materials remain in use for as long as possible through durability, repairability, reusability, remanufacturing, and recycling are within the scope of the circular economy (Stahel, 2016). Regenerating valuable and difficult-to-grow nutrients, returning them to nature, and supporting biological life instead of threatening it are also included under this strategy (Geissdoerfer et al., 2017). In the service sector, it encourages circular steps such as product take-back.

This strategy aims to promote efficient resource use and minimize waste and pollution (Ghisellini et al., 2016). This will lead to significant reductions in greenhouse gas emissions and resource depletion. It has the potential to create new economic opportunities through innovation, new business models, and reduced costs associated with raw material extraction and waste disposal. By keeping products and materials in use for longer periods, it increases resource security and reduces dependence on limited resources (Korhonen et al., 2018). It supports socially fair labor distribution and improves product safety. However, there are also various challenges in the circular economy. Since collaboration between designers, manufacturers, policymakers, and consumers is required, systematic commitment is needed throughout the value chain (Bocken et al., 2016). Advanced technologies and infrastructure are needed for recycling, remanufacturing, and waste management, which can be costly and time-consuming.

When investigating how the circular economy is applied specifically to the use of thermoplastic and wood materials, it is known that thermoplastics are very harmful to the environment due to their petroleum-based nature, and recycling processes must be managed well. In this context, the use of recycled and bio-based polymers gains importance under this strategy (Hopewell et al., 2009). Designers and manufacturers need to design and develop products with a focus on recycling. Within this framework, it should be planned where the recycled material will be used. Designing products made of thermoplastic materials specifically for recyclability involves selecting materials that can be easily separated and recycled, avoiding additives that hinder recycling, and designing for easy disassembly. The circular economy strategy for wood materials, on the other hand, is that wood materials are naturally sourced materials, so they are easier to renew and less harmful in terms of environmental impact (Goldhahn et al., 2021). However, forest management and the processes of obtaining wood, the protection of biodiversity, the chemicals used in wood products, and the lifespan of the resulting product are important points for the circularity of wood materials (González-García et al., 2009). Designing wood products for durability and longevity requires high-quality materials, but it is considered a sustainable approach because it reduces emissions from replacement and production in the long run. In this approach, the design factor of part-based disassembly is extremely important. It should provide the potential for repairing damaged parts instead of replacing the entire product.

In this context, the circular economy is a sustainability strategy that promotes efficient resource use, reduces waste, and aims to minimize environmental impacts. The circular economy approach, combined with CE certification and LCA analyses, can offer a comprehensive approach from a sustainability perspective.

2.7. Examining Strategies in Terms of Scope and Impact

The main sustainability strategies encountered during the literature review were addressed, and each was examined in detail. These strategies were: EU Ecodesign, Cradle to Cradle, Life Cycle Assessment, Eco Label, Sustainability in CE Certification, and Circular Economy. The details of these topics were examined, and it was found that each topic has a specific scope and area of impact. Within this framework, the strategies were analyzed in terms of their impact and scope.

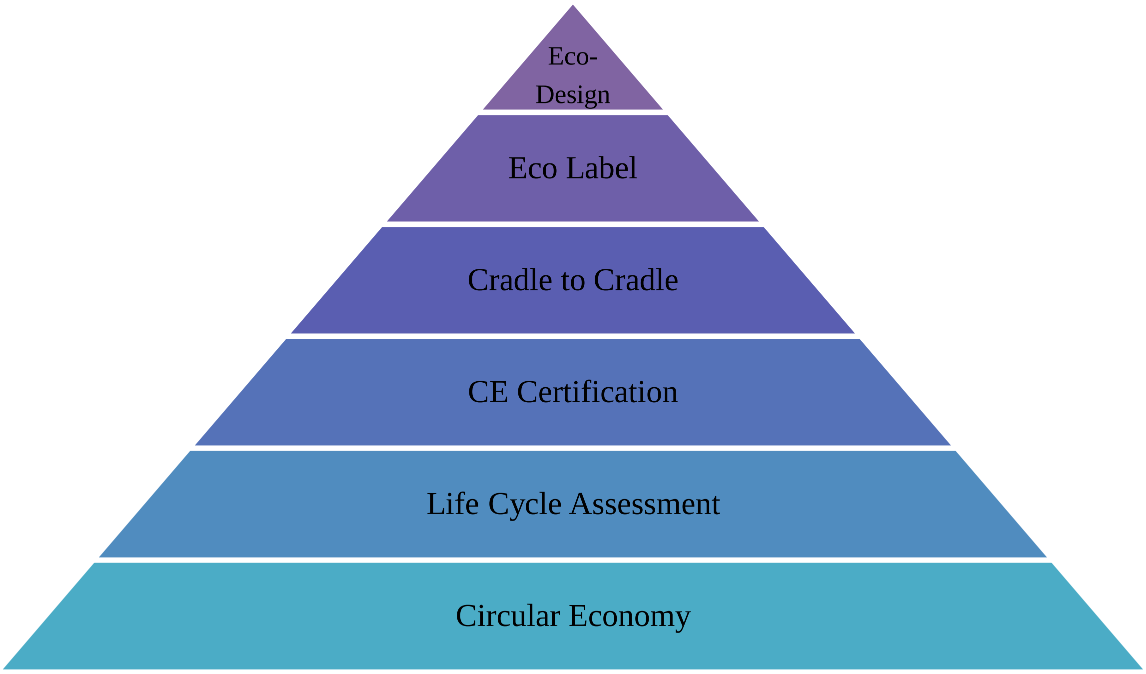


Figure 2.1. Examining the Scope of Strategies (wide to narrow)

Based on the strategies, the visual presented in Figure 2.1 emerged. The circular economy strategy has the broadest scope because it is applicable to many areas, including social aspects and physical products (Börkey and Laubinger, 2021). Life Cycle Assessment is placed in the second stage because it should be present in all kinds of physical products. CE Certification is placed third because it is required for products to be exported to the EU and to be placed on the EU market, and it is one of the oldest certifications. Also, its scope is broadened because it also requires Life Cycle Assessment. The Cradle to Cradle strategy is placed fourth because it specifically addresses topics such as product material health, water and soil management, and social equality and justice. Eco Label is placed fifth because it is not as new as Ecodesign, it constitutes an established strategy, and it covers many products, from physical products to products containing software. According to the Ecodesign 2009 directives, it has the smallest scope because it only covers products that operate with energy.

When the strategies are examined in terms of impact, the target market is divided into two: EU and global. It is understood from the literature that the EU market is large enough to have its own unique strategies and certification processes.

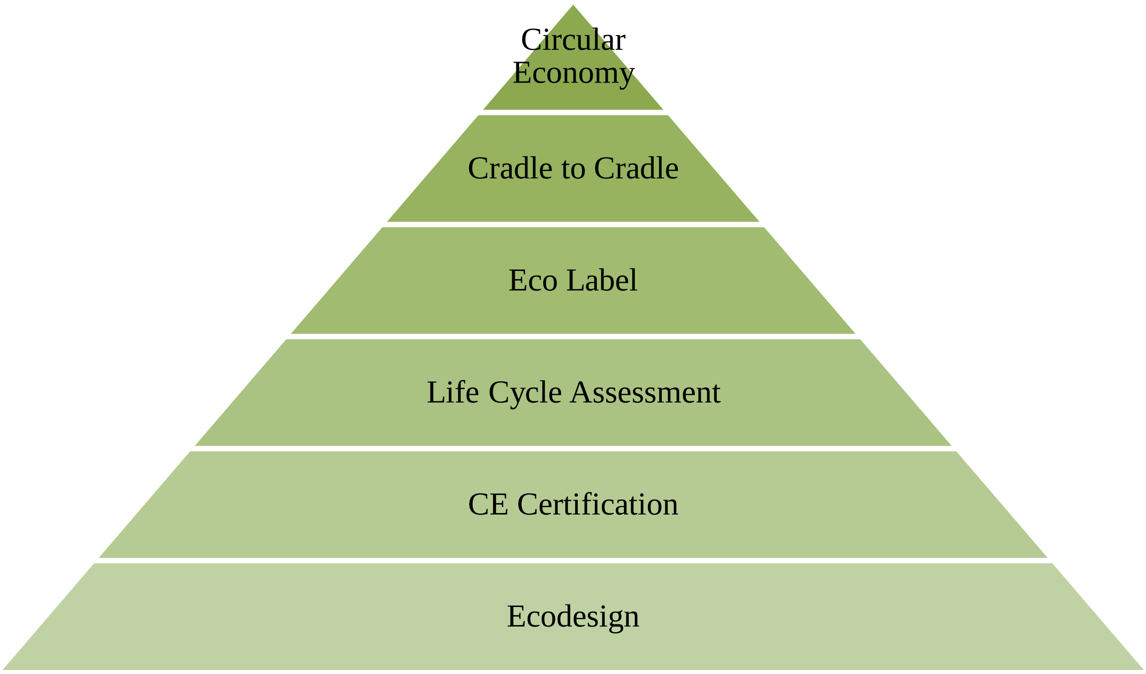


Figure 2.2. Examining the Impacts of Strategies on the EU Market in Terms of Size

Within the European Union, Ecodesign is one of the most effective strategies. Figure 2.2 shows the detailed area of impact from largest to smallest in the European market. Compliance with Ecodesign is a requirement within the framework of EU regulations (Börkey and Laubinger, 2021). This makes the Ecodesign strategy the most important. Another highly effective strategy is CE marking. This certification facilitates the circulation of the product within the EU market. Since Product Life Cycle Assessment is also required during CE marking acquisition, it is the next most important strategy. Eco Label is a strategy that the EU covers, ranging from software to physical products, from the food sector to the materials sector. Its certification can be obtained voluntarily, allowing the product to gain a market advantage. The Cradle to Cradle strategy is a strategy of an institute established through personal efforts. Here, the area of impact has been expanded through the influence of certain brands and institutions. The circular economy has a general scope, but there is no direct area of impact that appears under this name. It is embedded in many strategies (Börkey and Laubinger, 2021), but it does not exist as a direct circular economy label or certification.

2.8. AC Electric Vehicle Charging Stations and Material Used to Produce

Electric vehicle (EV) charging stations are divided into two types, AC and DC, based on the technology they contain. AC, which stands for alternating current, refers to the periodic change in direction of the flow of electric charge; therefore, everyday products such as household appliances use AC (LG Solar, 2019). DC, on the other hand, stands for direct current; in DC, the direction of flow does not change, and a more stable voltage is provided, which is why technologies that operate with high voltage are powered by a DC power source (LG Solar, 2019). Consequently, EV charging station technology is also divided into AC and DC. Charging stations that can provide fast charging and are used for commercial purposes are DC, while charging stations that can be used for commercial purposes or connected to household electricity, generally referred to as slow chargers, are AC (Savari et al., 2023). In this context, EV charging stations are divided into Levels 1, 2, and 3 according to their capacity. Level 1 refers to AC charging stations with a capacity of up to 120 volts; in general terms, it is referred to as the slowest charging level (U.S. Department of Transportation, 2023). Level 2 refers to AC and capacities up to 240 volts; at this station level, a fast AC charging process (average 4 hours) can be provided, and Level 3 covers DC charging stations (U.S. Department of Transportation, 2023). These are charging stations that can perform charging in a short time, such as 20 minutes to 1 hour, and are commonly referred to as fast chargers.

Electric Vehicle (EV) charging stations, especially AC charging stations, are critical components of the infrastructure supporting the transition to electric mobility. The importance of electric vehicles in the market is increasing due to the widespread use of electric vehicles. The importance of EV charging stations in the global industry is becoming even more significant for a sustainable world, depending on market demand. Therefore, when carrying out a case study of AC electric vehicle charging station design with a sustainable design strategy, the charging stations used in the European market and the main materials that make up these charging stations constitute a critical topic that needs to be investigated.

Through research, the Charging Report 2024 from the organization GridX was accessed, and since the target market is Germany, the main charging station manufacturers based on charging sessions were identified. These were: EnBW with 5.1%, E.ON Drive with 3.6%, Tesla with 2.3%, EWE GO with 2.1%, and Lidl with 1.7% (GridX, 2024). As the product group for the case study within the industrial collaboration is an AC 22 kW charging station due to the lack of diversity in the German market, the AC 22 kW products of these brands and the main materials used in the design of these products were examined as part of the literature review. While there is no directly publicly available material information for the KEBA KeContact P30 c-series Wallbox product, which is actively sold by EnBW and has these characteristics, there is information that the products are manufactured with the goal of sustainability and reducing the carbon footprint (KEBA, 2024). Literature research revealed that E.ON Drive, EWE GO, and Lidl are charging station operators and do not produce their own products, and Tesla produces AC charging stations up to 11.5 kW. This situation shows a market gap in 22 kW AC charging stations, indicating that the study is focused on the right target. Material data for the companies mentioned in the literature review could not be found, but it was observed that detailed material information for the products of Schneider Electric, one of the largest electronics companies in Europe, is publicly shared. Such moves, which are associated with a true understanding of sustainability, show that the company's sustainability data is transparent and realistic. Within this framework, the material details used in Schneider Electric's Schneider Charge product were accessed.

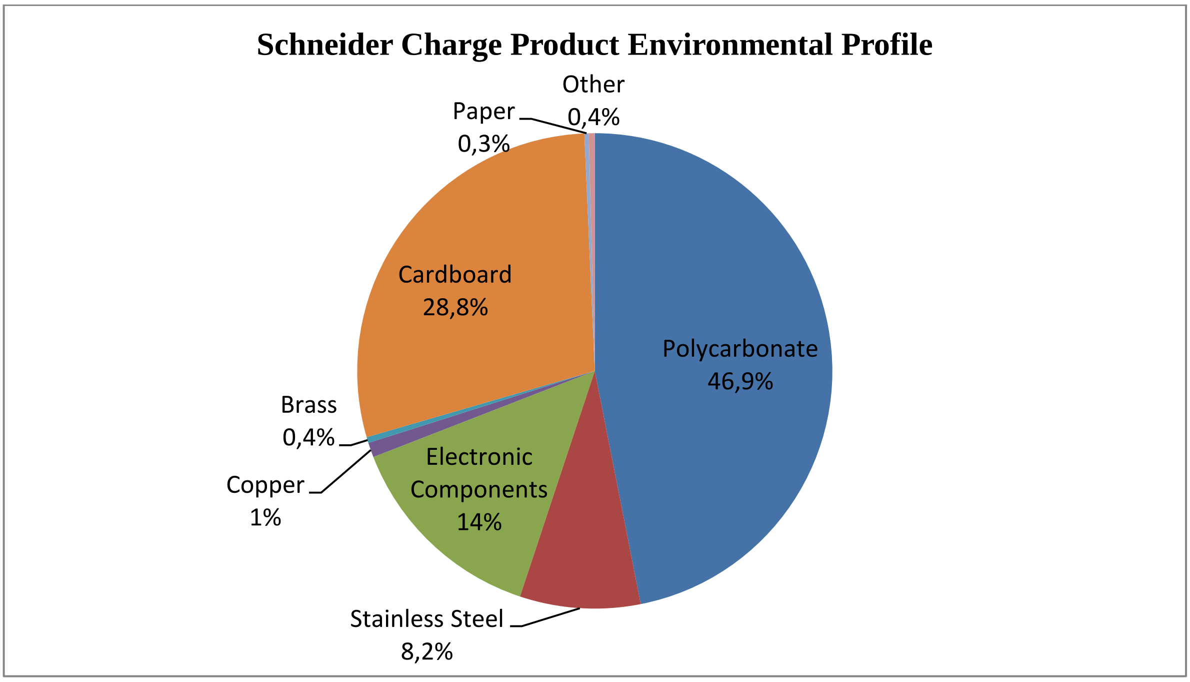


Figure 2.3. Percentage Distribution of Parts/Materials by Mass for Schneider Charge Product

Source: (Schneider Electric, 2023)

According to the data obtained, the Schneider Charge product has an average mass of 4780 grams, including packaging. As shown in Figure 2.3, when the material distribution is analyzed in percentages, it is seen that 2241.82 grams of polycarbonate material is used to form the product body, 1376.64 grams of cardboard material is used for packaging, 669.2 grams constitute the mass of the internal electronics, 391.96 grams consist of stainless steel, 47.8 grams are copper material, 19.12 grams are brass material, 14.34 grams constitute paper material, and the remaining 19.12 grams consist of various materials (Schneider Electric, 2023).

3. MATERIALS AND METHODS

In this study, where sustainable design strategies were investigated in terms of their global impact and scope, it was aimed to realize an exemplary sustainable product design by establishing a university-industry collaboration environment. Various methodologies will be applied to design a 22 kW AC electric vehicle charging station to be designed for the German market. The resulting case study will provide guidance for companies in Türkiye and identify areas where sustainability practices in product design can be improved, as reflected in the global literature. In the case study, the collaborating company will provide constraints related to internal electronic components and product dimensions, ensuring a realistic foundation for the research.

All companies that will develop or design products in line with sustainable product design are expected to start from the stage of selecting a design strategy. When considered in terms of impact and scope, these strategies become clear according to the objective. Once a sustainable design strategy is chosen based on the product's target market, the remaining steps of the case study can be implemented. In this study, various methodologies will be applied along with the determination of the design strategy. First, concept designs will be developed by applying the design thinking methodology according to the design strategy. Then, detailed House of Quality applications will be carried out, and the appropriate concept will be selected in cooperation with the company with which the industrial collaboration is established. At this point, concept selections will be left to the collaborating company, and the results are expected to be more realistic from an industry perspective. To select the main material that will form the outer shell structure of the product, basic material properties will be investigated, and parameters such as mechanical and thermal properties, and price of the material or materials will be revealed. In addition to these parameters, raw material emission data for the materials will also be added. Emissions from paints, surface treatments, and insulation chemicals have not been included in the study, as the focus of the study is on design and material selection, and the literature in this field is not yet mature in Türkiye.

Optimal material selection will be achieved by considering the product's mechanical and thermal performance, the price-performance ratio, and ecological sensitivity parameters. At this point, the Rule of Mixtures method will be applied to select and compare the main materials. Testing material mixtures using computer-aided analysis represents another method to be applied. The effectiveness of the mechanical and thermal performance of the specified mixtures in the product design form, and the degree to which they produce reliable results, will be revealed through static analysis with safety factor values. Thus, material selection for product design can be made based on mechanical and thermal performance, price, and ecological sensitivity. In this way, concrete and guiding steps will be practically revealed regarding the shape of the designed part and how material mixtures should be selected in terms of ecology and performance. At the end of the study, a physical model will be produced to see how well the methodologies to be applied will yield reliable results.

While carrying out the steps mentioned for the case study, Blender software will be used in the concept design phase. Blender is an open-source 3D creation software. Autodesk Fusion 360 software will be used for engineering design and computer-aided analysis activities. This software is free for academic studies and paid for industrial use. CCaLC 2 software will be used for carbon emission calculations for materials, and access to the EcoInvent Material Database will be provided through this software. The data set shared by ANSYS for educational purposes will be used for material properties.

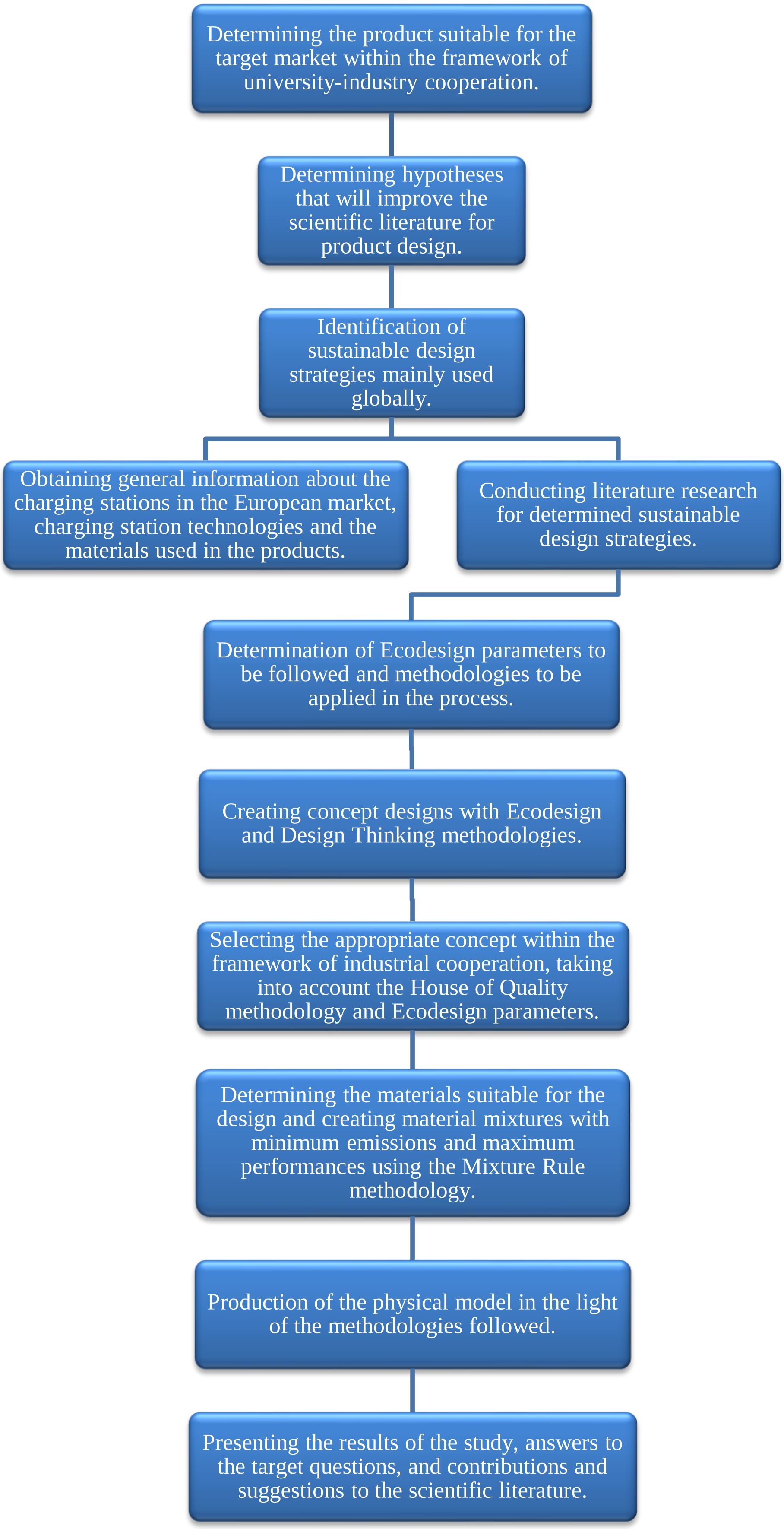


Figure 3.1. Flow Diagram of the Processes within the Scope of Work

It can also be seen in the flow diagram presented in Figure 3.1, the process began with the identification of major sustainability strategies in the global literature, prior to the literature reviews. Then, by researching this literature data, the breadth of sustainable design strategies in terms of impact and scope, and their target regions, were obtained in detail. It was understood from the literature reviews that the most effective strategy within the borders of the European Union is Ecodesign. It was observed that the broadest and most comprehensive strategy in terms of scope is the Circular Economy strategy. When products in the European market were examined, the most detailed material data was obtained from the Schneider Charge product. It was observed that this product uses 2241.82 grams of polycarbonate material (Schneider Electric, 2023). It was observed that this product, which uses polycarbonate material, complies with the Restriction of Hazardous Substances Directive (RoHS). Within this framework, it was intended to carry out a case study of sustainable product design by applying the steps in the flow diagram.

3.1. Sustainable Design Strategy

With the development of technology and the sustainability literature, sustainable design strategies are also increasing day by day. Different approaches are presented by various institutes and organizations and are increasing their popularity in the public eye. For the study to be carried out, the most suitable sustainable design strategy in terms of impact and scope must be selected and used in the case study. The strategies investigated within the framework of the literature review were: Ecodesign, EcoLabel, Cradle to Cradle, Life Cycle Assessment, CE Certification, and Circular Economy. Accordingly, since the product is to be used in Germany and the Ecodesign strategy is further strengthened by new EU regulations in terms of its impact area, it was decided to continue the study with the Ecodesign strategy.

The Ecodesign strategy is a strategy created based on the principle of reducing resource use by ensuring energy efficiency of the product, and today, with various updates, it has come to include deeper constraints in the product design strategy. Making products more environmentally friendly and nature-friendly through constraints such as energy efficiency, resource efficiency, durability, long-term use, circular economy, and recyclability are included within the scope of this strategy (Dalhammer et al., 2014). It is possible to create products that are more compatible with the Ecodesign strategy through parameters such as the use of non-toxic materials, renewable materials, recycled materials, and recyclable materials in the material selection stages (Zbicinski et al., 2006). The features brought by the Ecodesign strategy in terms of product characteristics are: long-term product use, repairability, recyclability and end-of-life management, material efficiency, and upgradability (being able to upgrade the product's features without discarding it).

Table 3.1. Parameters within the Framework of the Ecodesign Strategy to be Implemented

Material Based Parameters	**Product Based Parameters**
Non-Toxic Materials	Longer Lifespan
Renewable Materials	Repairability
Recycled Materials	Recyclabilibty
Recyclable Materials	Material Efficiency
	Upgradability (Through modularity)

Within the framework of the planned strategy, it is aimed to comply with the Ecodesign strategy by determining the parameters given in Table 3.1. Compliance with the Ecodesign strategy can be achieved by creating a design that adheres to at least one of the material-based parameters and all of the specified product-based parameters.

3.2. Design Thinking Methodology and Concept Design

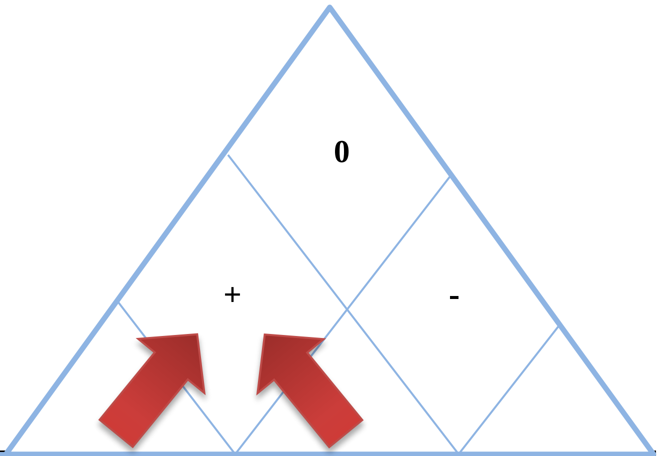
The design thinking methodology will be applied to design the form and create the concepts. Within this framework, 5 concept designs will be prepared, and the course of the design will be determined. This stage is critically important for the design of the form. It constitutes the phase where product features such as creativity and functionality are defined in the design. Although different steps are followed when applying the design thinking methodology, the main headings are generally: research, ideation, and prototyping (Vianna et al., 2012). In the research phase, the scope of the problem is examined in depth. Answers are sought for the questions known as 5W1H: what, where, how, why, when, and who (Yang et al., 2019). Design constraints are stated, and the direction of the design is guided at this stage. The answers obtained as a result of the research are considered as parameters, and concept drawings are started in the ideation phase. Since these parameters become new constraints of the design, the concepts must be made accordingly. Then, the resulting concept designs are produced as physical models in the prototyping phase, allowing the designs to be seen in a real way (Björklund, 2019). If necessary, the revision phase of the concept designs is started after this model production. Thus, answers such as whether the design complies with the constraints, the quality of the design and the lines can be reached by producing a physical model. However, in this case study, the physical production in the prototyping phase of the design thinking methodology will not be applied. By transferring the concept designs from 2D to 3D in a computer-aided design environment, the designs will be visualized in grid space, thus avoiding physical production at the concept design stage, reducing plastic use and production-related emissions.

The storyboarding technique will be used for this methodology to derive results. The number of different form concepts to be designed, which is five, is not a constraint or a part of the design thinking methodology; institutions or individuals who will take this study as an example can increase or decrease the number depending on parameters such as their resources, capabilities, and the number of expert personnel. Increasing the number of different form concepts means approaching perfection, while decreasing this number will make the study more superficial.

3.3. Concept Selection with House of Quality Methodology

Once the concepts are designed, the most suitable concept must be selected rationally. For this selection, a method called the House of Quality methodology will be applied. To reflect the industry perspective, the company with which the industrial collaboration is established will be asked to score the concepts using the House of Quality. The House of Quality is used today as a part of quality function deployment for rational weighting and selection, and it is included in the literature as part of market research techniques (Hauser, 1993). In terms of its application, the characteristics in the rows and columns, consisting of "what" and "how" questions, are cross-referenced, and the relationship is scored using values such as 1-10 or 1-5 (Manchulenko, 2001). Generally, the rows are parameters that answer the "what" question, and the columns are parameters that answer the "how" question, and the triangular roof section in Table 3.2 represents the relationships (positive, negative, neutral) between them. From a different perspective, considering customer needs and technical requirements, the rows represent the "what" question, i.e., customer needs, and the columns represent the "how" question, i.e., technical requirements, forming a methodology that can be used for selecting prominent features. However, in this study, since it will be used for design selection, not feature selection, the "how" question will be replaced by designs, and the "what" question will be replaced by technical criteria. Therefore, the roof section seen in Table 3.2 will not be applied in the study, and it will not represent data that should have a relationship direction between the designs. Also, the rows labeled 'Customer Request' will be replaced by technical criteria.

Table 3.2. Sample House of Quality Table with Visual Explanation



	Importance Level	Design A	Design B	Design C
Customer Request 1	D_1	P_1	P_5	P_9
Customer Request 2	D_2	P_2	P_6	P_{10}
Customer Request 3	D_3	P_3	P_7	P_{11}
Customer Request 4	D_4	P_4	P_8	P_{12}
Absolute Importance		M_1	M_2	M_3
Relative Importance (%)		B_1	B_2	B_3

The legs of the roof section shown in Table 3.2 indicate the column boxes in the direction of the arrow, expressing the relationship between them as positive (+), negative (-), or neutral (o). According to the relationships, technically, rows and columns are cross-referenced, and the total values are written in the bottom row.

In this study, the scores in the section called importance level, i.e., the values expressed as 'D', and the values expressed as 'P' in the columns such as Design A, B, C, will be given by the company within the industrial collaboration, based on the concept designs to be created. The scores will take values between 1-10, where 'M' represents the total column values, and 'B' represents the percentage weight of the design within the total study. For example, the M2 value is calculated as shown in Equation 3.1, determining the absolute importance score:

$$\sum M_2 = (P_5 \, x \, D_1) + \ (P_6 \, x \, D_2) + (P_7 \, x \, D_3) + (P_8 \, x \, D_4) \quad (3.1)$$

To calculate the relative importance, such as a B3 value, first, the total M is found as shown in Equation 3.2:

$$\sum M = M_1 + M_2 + M_3 \tag{3.2}$$

Then, for the B_3 percentage, the calculations expressed in Equation 3.3 are applied to calculate the relative importance values:

$$For\ B_3\ percentage, \frac{M_3}{\sum M}\ x\ 100 \tag{3.3}$$

Under these conditions, by applying the House of Quality methodology, the most suitable design can be selected based on the weighting of the parameters within it through scoring (Güllü and Ulcay, 2002).

3.4. Material Selection, Carbon Emissions and Rule of Mixture Approach

Following the concept selection phase, the critical stage of the study, material selection, will begin. For material selection, it is observed in the literature that the main material of many electric vehicle charging stations is acrylonitrile butadiene styrene (ABS) and polycarbonate (PC), and their selection is appropriate in terms of both resistance to atmospheric conditions and cost-performance (Canbulat & Savaş, 2023; Mura et al., 2018). However, the mixture ratios will be determined using the Rule of Mixtures methodology, which will be applied for material selection, to determine whether 100% ABS or PC will be used directly. The study will proceed with the material data set shared by ANSYS for academic purposes to be used in computer-aided design and analysis.

Table 3.3. Properties of ABS and PC Materials Provided by ANSYS

Mechanical Properties	Density (kg/m^3)	Tensile Strength (MPa)	Yield Strength (MPa)	Young's Modulus (GPa)	Fracture ($MPa.m^{1/2}$)	Price (US Dollar/ kg)
ABS	1100	41.5	35	2	1.2 - 4.3	2.55
PC	1150	66	64.5	2.2	2.1 - 4.6	4.85
Thermal Properties	T_g(°C)	Specific Heat (J/kg.°C)	T Conductivity (W/m/K)	T Expansion (10^{-6}/°C)	Resistivity (µohm.cm)	Dielectric Constant (-)
ABS	88 - 130	1650	0.265	85 - 230	3.3 $x10^{21}$- 30 $x10^{21}$	3
PC	140 - 200	1550	0.205	120 - 140	100 $x10^{18}$- 1 $x10^{21}$	3.2
Environmental Properties		Energy (MJ/kg)		Carbon (kg/kg)		Water (L/kg)
ABS		95		3.8		180
PC		105		6.05		175

Table 3.3 presents the data set shared by ANSYS (Ashby, 2021). In the data set, data such as mechanical, thermal, environmental properties, and price for the main materials planned to be used in the study were obtained. After this point, the necessary definitions of these properties for ABS and PC materials will be provided in Autodesk Fusion 360.

When the EcoInvent Material Database was accessed through CCaLC 2 software, more comprehensive carbon data for ABS and PC materials were obtained.

Table 3.4. ABS and PC Material Emission Values via EcoInvent Material Database

Raw Material	Amount (kg)	CO_2 equivalent factor (kg/kg raw material)	CO_2 equivalent (kg)
ABS	1000	4.40	4403
PC	1000	7.79	7788
Total:	2000	**Total:**	12191

Looking at the emission values shown in Table 3.4, unlike the ANSYS data, not only carbon values are given, but a unit including CO_2 equivalent and other greenhouse gases is used. This situation has been informative in terms of the magnitude of other greenhouse gases calculated alongside carbon emissions. When calculating the Total CO_2 equivalent data in Table 3.4, the following equation was used:

$$\sum CO_2 eq. = Amount\ x\ CO_2 eq. \tag{3.4}$$

where CO_2eq. represents the CO_2 equivalent factor (Canbulat & Savaş, 2023). Thus, the total emission amount in terms of CO_2 and equivalent gases can be calculated by multiplying the emission value coefficient of the material by the amount used.

In the material selection methodology, the Rule of Mixtures methodology will be used to access various material properties based on mixture ratios and to analyze these various properties through computer-aided analysis. According to the Rule of Mixtures methodology, properties increase or decrease proportionally to the mixing ratio of the material (mixing in pellet form). This situation opens the way to calculating mechanical, thermal, environmental, and price properties in proportions of 1 and 9 in cases where 10% ABS and 90% PC materials are mixed. Adding 1/10 of the tensile strength of ABS and 9/10 of the tensile strength of PC to obtain the new tensile strength expresses the basic logic of this methodology. Expressed as an equation, the equation seen in 3.5 is applied:

$$\sigma = (\ \sigma_A\ x\ V_A\ ) + (\sigma_B\ x\ V_B\ ) \tag{3.5}$$

where σ_A represents the property to be predicted in material A, multiplied by V_A (percentage value, for example; 40/100), meaning the property of material A is multiplied by the mixing ratio to indicate how much value is taken from that material, and σ represents the value of the calculated property for the mixed material (You et al., 2017). The terms represented by B indicate the other material in the mixture. However, there is a problem with the Rule of Mixtures methodology. The Rule of Mixtures is a methodology designed to predict material properties before mixing, and the prediction of each property is not solely dependent on the mixing ratio. Therefore, it was understood that it is possible to predict the following properties according to Table 3.3 in two different granular thermoplastic materials to be mixed by applying the Rule of Mixtures methodology: density, tensile strength, yield strength, Young's modulus, price, and greenhouse gas emissions (You et al., 2017; de Gortari et al., 2020; Zare & Rhee, 2018).

3.5. Safety Factor and Material Defined Part Analysis

After determining the properties of the material mixtures using the Rule of Mixtures methodology, it is necessary to proceed to the computer-aided analysis, or computer-aided engineering, phase. In this phase, static stress analyses will be applied to the designed part using Autodesk Fusion 360 software. During the analysis process, material variants and their properties, created using the Rule of Mixtures methodology, will be defined in the software through the new material definition screen. When determining material variants, the Rule of Mixtures methodology will be applied with 10% increments, and if very similar result values are found in the analysis results, more precise calculations will be made with increments of 5% and 1%. Thus, the most effective mixing ratio will be determined.

The coefficient called the safety factor is a data point that can also be revealed in static stress analysis, and it represents a rating that shows the state of the analyzed part or parts under a defined load. In this rating, areas with a value of 1 and below indicate the weak points of the part, areas with a value between 1-3 indicate acceptable but not fully performing areas, areas with a value between 3-6 indicate that it will show the most effective strength, and areas with a value of 6 and above indicate that it is unnecessarily good (Fiedler, 2018). The safety factor can be calculated as shown in Equation 3.6:

$$SF = \frac{MS}{AS} \tag{3.6}$$

where SF represents the safety factor, MS represents the material strength, and AS represents the applied stress. In this calculation, the value represented by MS will be the yield strength of the material, thus revealing the situations where the material will undergo plastic deformation or fracture under the specified stress (Rizki et al., 2024). When performing computer-aided analyses, the mass of the part will also change continuously in proportion to the defined material variants; the material densities will change continuously within the scope of the Rule of Mixtures methodology, and the mass will change even though the part size remains constant. The equation expressing this situation is shown in 3.7:

$$m = V \ x \ d \tag{3.7}$$

where m represents mass, V represents volume, and d represents density (Hawkes, 2004). As stated, while the part size, V, is constant, changes in the d value will change the part mass, m.

One of the critical points in computer-aided analysis applications is the definition of analysis constraints. Since the safety factor value will be determined according to the stress that will occur, what the analysis constraints are and how they are defined is of great importance. According to the product's usage, the part mounted on the wall will be defined as a fixed point in the analyses, and if necessary, the analyses will be carried out at a reference room temperature of 25 °C (Shackelford, 2014). Gravity definitions will also be made in the analysis, and its value will be 9.807 m/s². In the analyses, the direction of the force to be applied to the product will be applied from all directions, namely along the X, Y, and Z axes, including the + and – surfaces, and no force will be applied from the fixed part. When looking at the force magnitudes, a total value of 1000 N will be applied from these directions.

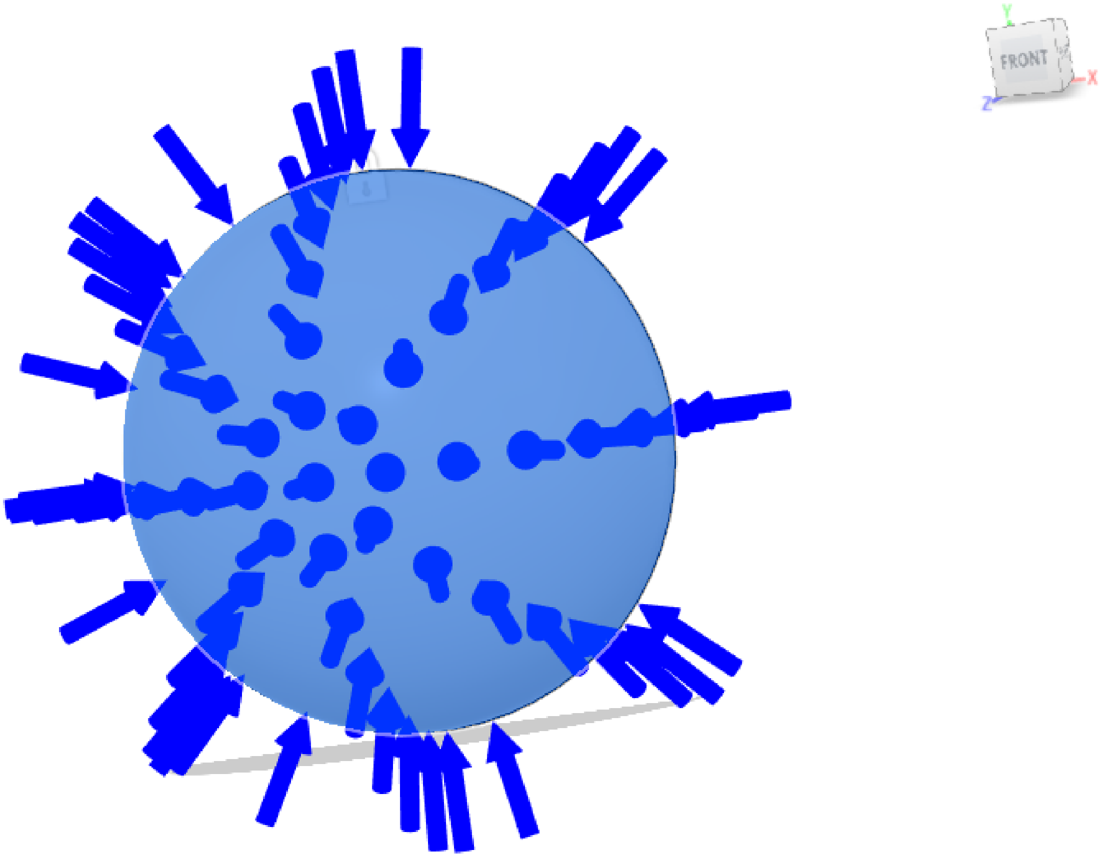


Figure 3.2. Direction of Application of Forces in Analysis

Forces will be applied in the arrow directions shown in Figure 3.2. Since the back part is the fixing point, no force will be applied from that direction.

4. FINDINGS

The methods to be used and the methodologies to be followed according to the flow diagram in Figure 3.2 have already been determined. In this chapter, the sequential application of the methodologies and the completion of the case study dimension of the work will be seen. The Ecodesign strategy, which is the strategy that should be applied in terms of impact and scope, was implemented along with the design thinking methodology, and five different concepts for the product were developed. In line with the opinions of the company within the industrial collaboration, concept selection was carried out using the House of Quality methodology, and at this point, the final version of the selected concept was determined based on the recommendations. Subsequently, a data set for material options was created, and analyses were performed on the finalized design. Material selections were made according to priorities, and it was demonstrated how the emissions of the product could be directly altered through industrial design. A physical model was produced according to the selections made, and the case study was completed.

4.1. Concept Designs Created With Sustainable Design and Design Thinking Methodologies

The Ecodesign strategy, determined as the basic design strategy for the case study, requires the product to be long-lifespan, repairable, recyclable, efficient in terms of material efficiency, and modular, allowing for later upgrades; that is, a modular structure where the external design remains the same and internal electronic components with different features can be integrated. Therefore, concept selection will be carried out considering these parameters, thus ensuring compliance with Ecodesign requirements. For this reason, these parameters will be defined for the scoring to be done within the scope of the House of Quality, ensuring that the concepts are selected in accordance with the requirements of the Ecodesign strategy. Another aspect of implementing the sustainable design strategy was that the material should be non-toxic, renewable, recyclable, or recycled. The fact that the scope of the study is limited to the disciplines of industrial design and sustainable design leads to the neglect of material-based Ecodesign parameters. At this point, ABS and PC materials emerge as an industry standard for the product determined due to electronic and engineering constraints and are also a constraint of the study due to the manufacturability requirements of the company with which the industrial collaboration is established. It has been observed in the literature that ABS and PC materials compliant with the EU Restriction of Hazardous Substances (RoHS) Directive also exist. Therefore, in the concept selection in the study, the product-based parameters of the Ecodesign strategy specified in Table 3.1 were considered, and selections were made.

The design thinking methodology has been a methodology where the design is guided and revealed by various parameters. The application of the design thinking methodology in this study was carried out by addressing the research and ideation phases. In the research phase, the answers to the questions known as 5W1H were determined. In addition to the answers given to these questions, there are also some elements that are constraints of the study. The study constraints determined to ensure a manufacturable and concrete study with the company with which the industrial collaboration is carried out were: internal electronic components, product dimensions, the necessity of using ABS and PC materials, manufacturability with plastic injection molding, design compatible with German timber-framed houses, a perception of an environmentally friendly product in the design, and the maximum mass of the shell structure being approximately 2240 grams.

Table 4.1. 5W1H Questions and Answers

Questions	Answers
What?	• 22 kW Electric Vehicle Charging Station
Where?	• Outdoors or garages • Compatible with rural areas of Germany (wooden houses in historical structural form)
How?	• AC • Type 2 Plug
Why?	• The widespread use of electric vehicles and their long charging times trigger the individual use of chargers at home.
When?	• Charging is a process that may be required 24 hours a day, in 4 seasons. Therefore, the product must be able to operate under various conditions.
Who?	• Users; Adults of all ages, every genders and every professions. • For individuals

The answers to the 5W1H questions asked for the research phase of the design thinking methodology are given in Table 4.1. These answers play an important role in shaping the design during the ideation phase.

Table 4.2. Electronic Parts, Mass and Dimension Information Given as Restrictions

Part Name	Mass (grams)	Dimensions (width x length x height)
Main Electronic Parts	1798	210 x 210 x 95 mm
Protective Polycarbonate Sheet for Electronic Parts	55	180 x 85 x 3 mm
Type 2 Charging Cable	2000	Diameter 10 mm, Length 2.5 m
Electrical Connection Cable	355	Diameter 10 mm, Length 75 cm

Technical information regarding the electronic components provided by the company with which the industrial collaboration is established, in order to make the case study manufacturable, is given in Table 4.2. Engineering designs of the concept designs will be created based on this information. Compliance with this information is mandatory and is therefore defined as a constraint.

Within the scope of the ideation phase of the design thinking methodology, 5 concept designs were realized. The most suitable of the concept design studies, made based on the information given in Table 4.1 and Table 4.2, is selected using the House of Quality methodology, taking into account the parameters introduced by the Ecodesign strategy and the opinions of the collaborating company regarding manufacturability. User research was not conducted within the scope of the design thinking methodology, and data was provided by the collaborating company as a hypothetical user. According to this, the hypothetical user is defined as: 18-60 years old, male and female, middle and upper income level, high school education or higher, living in or near the city, electric vehicle owner, wanting to easily charge their electric vehicles at home, expecting the product to be long-lasting, reliable, durable, and repairable, and attaching importance to sustainability and recycling. All concepts were designed according to this hypothetical user.

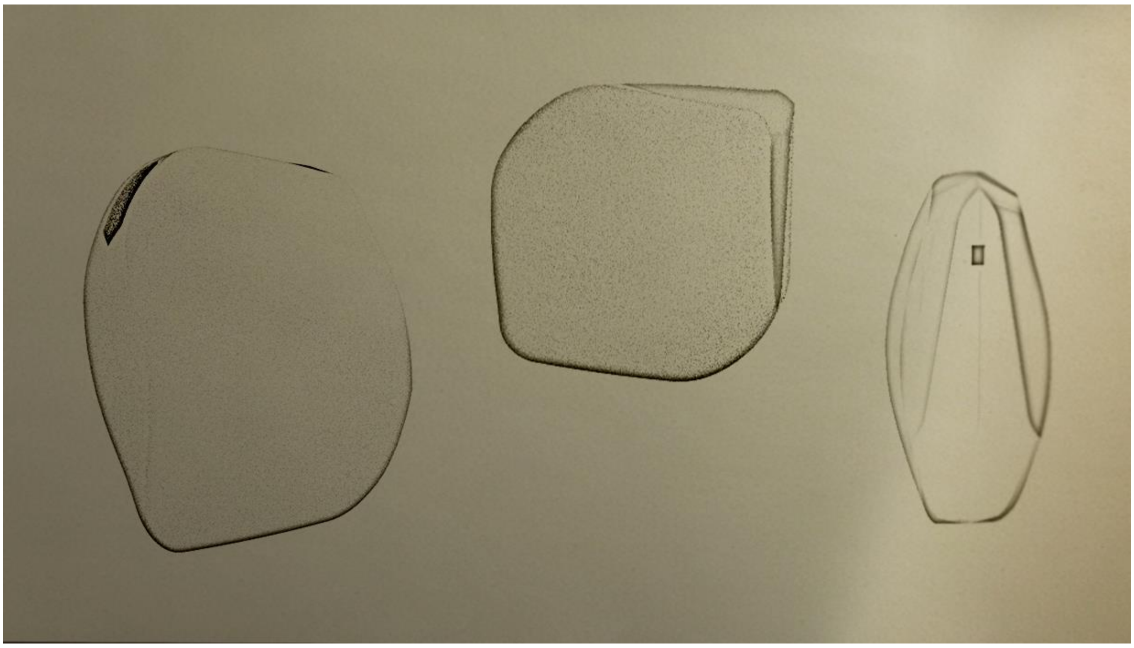


Figure 4.1. Sketches of Concept-1

A body structure design where the electronic components are gathered in the center of the form is shown in Figure 4.1. This concept, unlike the sharp lines and geometric forms of traditional German houses, creates a more organic and natural contrast. This contrast draws attention to the product while also emphasizing an approach that is in harmony with nature. It was designed in an organic form to meet the aesthetic expectations of our hypothetical user. The organic lines in the form provide a more flexible and wider area for the arrangement of internal electronic components. User safety is expected to be ensured by positioning the electronic components in a dedicated area in the center. It is thought to have a robust and modular design, as the part thickness is increased at certain points. Modularity refers to a single outer shell structure design that encompasses AC charging stations capable of charging at lower power levels, due to the spaciousness of the internal area. Furthermore, in the context of the relationship between modularity and repairability, the parts will be assembled together completely mechanically; therefore, in case of broken parts or damage to electronic components, disassembly can be performed, and damaged parts can be replaced. At the same time, since it will also include other AC charging station capacities, the repair process for the outer shell will be the same for all product groups. The main shaper of the design was compatibility with German traditional houses, answering the "where" question. It is thought that it can be more compatible with the Ecodesign strategy by being produced using recycled thermoplastic material.

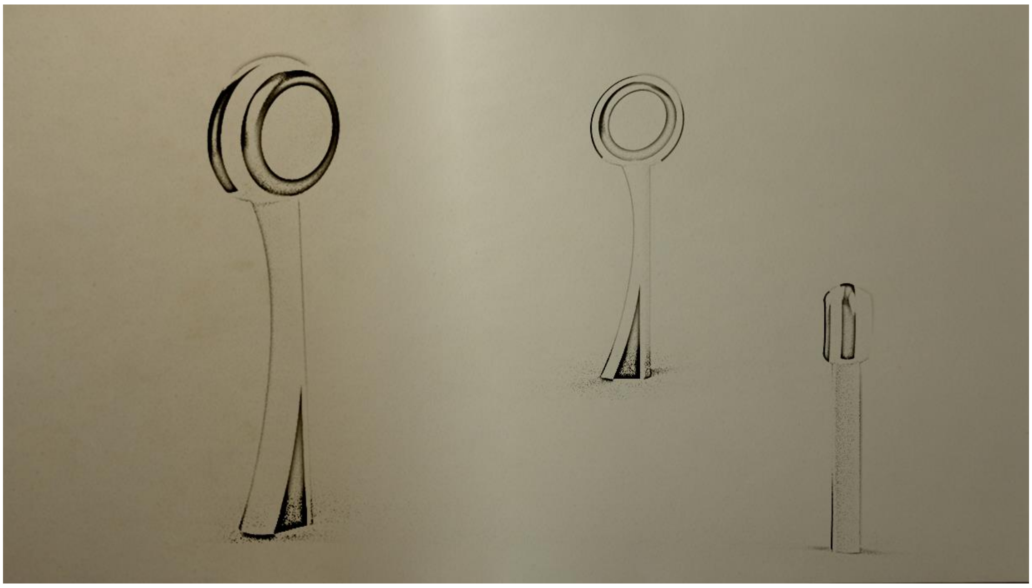


Figure 4.2. Sketches of Concept-2

A visual of the design, realized with a postmodernist design approach based on the idea of the sequential local structure of timber-framed houses, is given in Figure 4.2. The concept was designed with a postmodernist approach, referencing the asymmetrical harmony between the fences of timber-framed houses and the hanging signs in outdoor spaces. It is thought that with the colors to be defined for the product, it can adapt to a Medieval, Renaissance atmosphere, or modern environments. The "where" and "who" questions were influential in shaping this design. It has been an effective design for the target audience of German traditional houses and adults who want to see old tools and technology harmoniously intertwined. Metal use will be a necessity in this design, otherwise, problems with structural strength are expected. It is thought that the concept can be produced by using metal and thermoplastic materials together, and recycled metals can be preferred for the metal material. It is planned to consist of three parts: a metal base, and a thermoplastic head consisting of male and female parts. Thanks to the mechanical connection of all parts, it is thought that there will be no problem with repairability. However, modularity is not very efficient in this concept. Since the strength of the base part must also increase according to the mass of the internal parts, materials that will perform best and be used for a long time in the internal parts with the largest mass will need to be selected. The best performing foot will need to be chosen for the lightest body. This situation will increase emissions and costs. This concept was designed to meet the expectations of our hypothetical user for a long-lasting and reliable product.

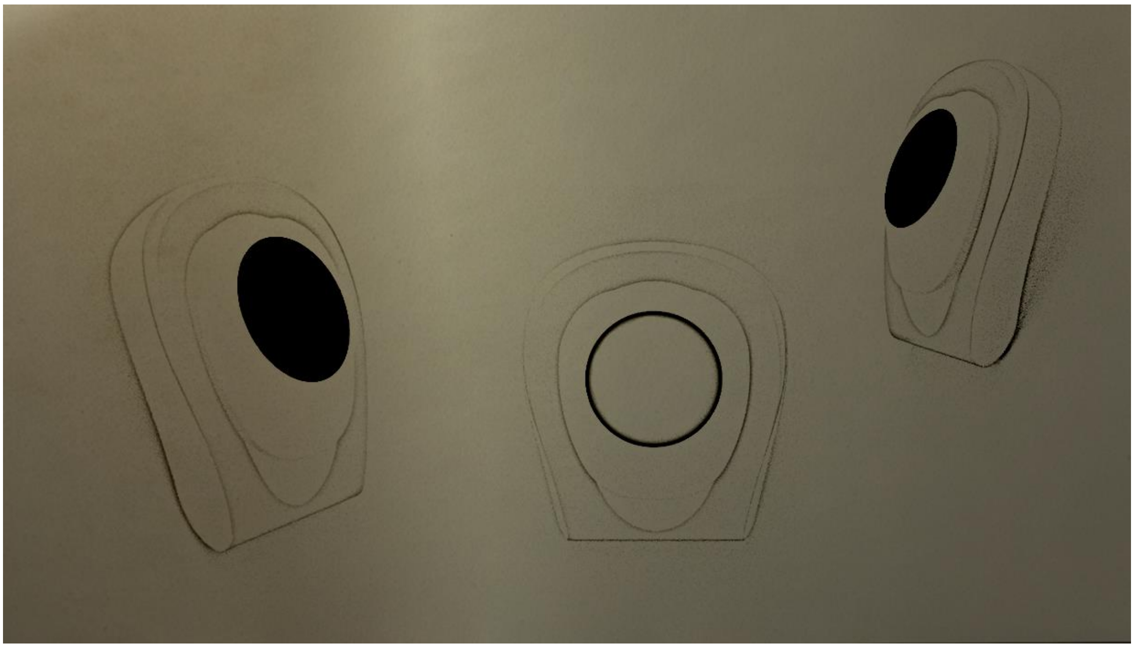


Figure 4.3. Sketches of Concept-3

Sketches of another concept, where a futuristic appearance with soft lines is sought, are given in Figure 4.3. This design features a circular screen on the front surface. Due to this screen, a perception of a technological form has been given. When smooth geometries and a curved form structure are combined, it highlights the perception of a high-tech product and gives the feeling that the product is made of plastic or metal. Therefore, the futuristic approach has been heavily weighted in this design. The "who," "how," and "why" questions are the main drivers of this design. The design was shaped in line with the need for adult users to charge their vehicles easily and ergonomically. The compact structure highlights the product's robustness and modularity. Unlike other concepts, the product will be created not by joining male and female parts, but by assembling three layered parts on top of each other. In this concept, where mechanical joining techniques will be applied, robustness and technology have been prioritized. In terms of repairability, the fact that there are more parts forming the shell structure and that the parts are smaller in volume will also reduce spare part emissions due to repairs. Since it can also accommodate lower-capacity AC charging technologies in a single body, compatibility with modularity is emphasized at this point. The use of thermoplastic material is planned for the general outlines of the concept. In order to easily adapt to the different needs of our hypothetical user, different technologies and interfaces can be integrated into this modular design. The use of recycled thermoplastics is possible in this concept.

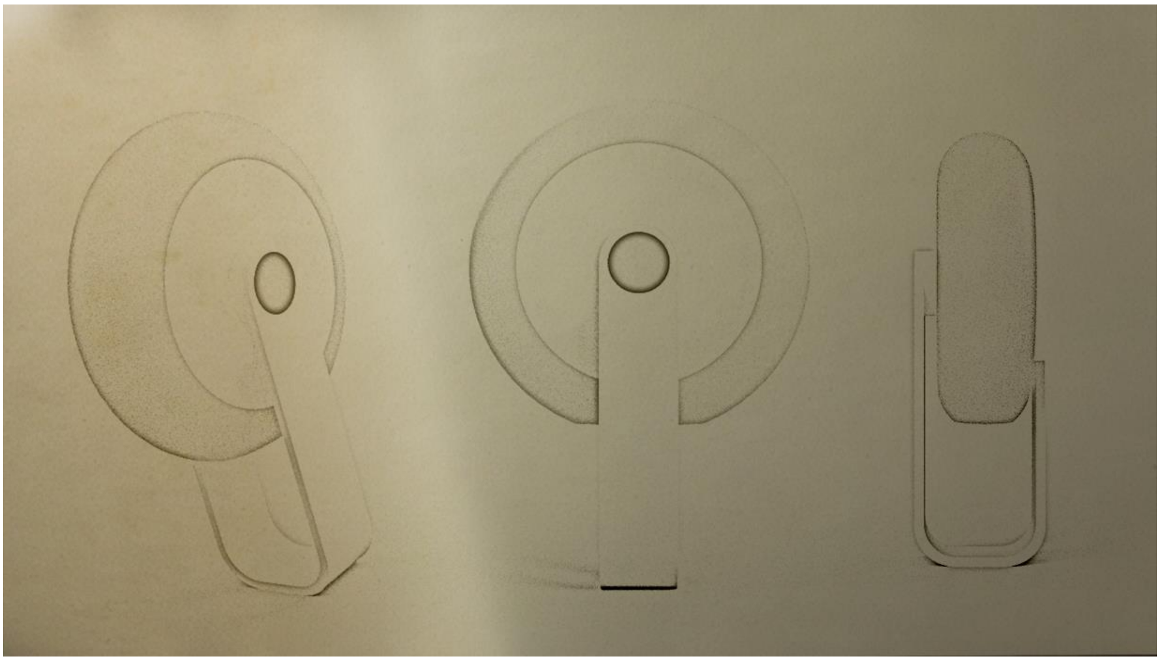


Figure 4.4. Sketches of Concept-4

Sketches of the concept, where a symmetrical and simple design approach is preferred as opposed to an asymmetrical structure, are given in Figure 4.4. While trying to offer a minimal approach that will not disrupt the natural appearance of traditional German houses, a form that is just as striking has been presented. In this context, the main shaper of the design was the "where" question. When simple colors such as wood texture for the arm structure and white tones for the main body are preferred, the perception that the product is an environmentally friendly product can be brought to the fore. It also seems possible to make the product futuristic with different color tones and light patterns to be added to the circular form. The minimalism of the form provides a comfortable space for the placement of internal parts. The concept is planned to consist of three body parts. These are: male and female parts in a shell structure for the body, and a single solid structure part for the arm. Since it is predicted that the part of the design that will be damaged is the load-bearing arm part, it is thought that the repair process will be carried out by replacing the wooden part, preventing emissions. Since a single body will also be used for technologies in other AC charging capacities, a modular design is also at the forefront in this concept. The use of thermoplastic for the body and wood for the arm part is considered. To meet the aesthetic expectations of our hypothetical user, this design was designed in a simple and minimalist form. Smooth geometries and minimal design have offered a design that supports the use of recycled/performance-degraded thermoplastics. Product strength can be increased by increasing the amount of performance-degraded materials in a way that supports durability in the internal design.

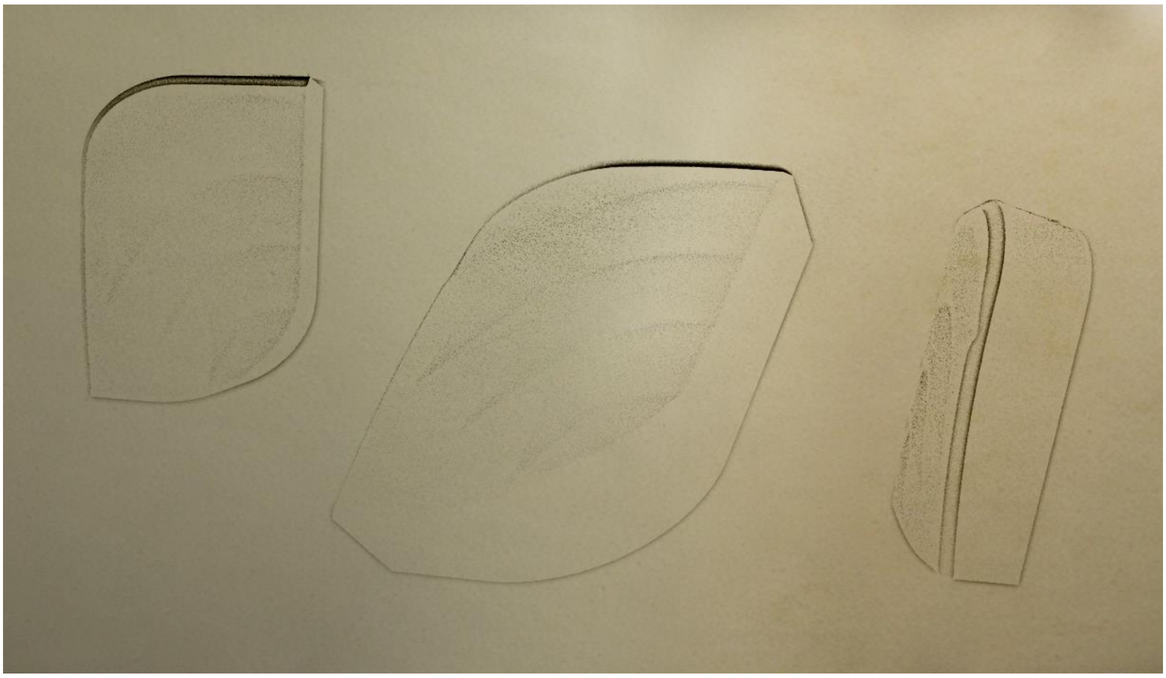


Figure 4.5. Sketches of Concept-5

A visual of the concept, which guides the user using an organic, fluid, and dynamic form, is given in Figure 4.5. This design, reminiscent of a leaf or a piece of rock, aims for an appearance that is in harmony with nature. Offering various forms when viewed from different angles, this design has a dynamic structure. The main lines of the design aim to offer users a natural and modern feel, while also presenting a striking aesthetic. The "where" and "when" questions were the main drivers of the design. While emphasizing German traditional houses and forests, the design emerged with a reference to spring leaves due to the abundance of forests in Germany. Different combinations can be achieved with white and gray tones in the main body and prominent color tones such as green on the edges, making it a product suitable for both modern and historical places. The fluid form is thought to increase the mechanical performance of the product. It has a body design that will be highly compatible with electronic components. Considering the environmental sensitivity of our hypothetical user, it is a design suitable for the use of recycled thermoplastic material. Modularity is ensured by the single-body concept, due to compatibility with technologies in other AC charging capacities. The parts are thought to consist of two pieces in a shell structure, male and female. No joining method other than mechanical joining will be used, and repairability is also supported in this concept. In case of damage to electronic or mechanical parts, repair can be provided by performing disassembly at the mechanical joining points. Since the same design will be applied to the mechanical parts with product groups of other capacities, the process will generate less financial expenditure. It was considered that recycled thermoplastic material could be used for the general product outlines.

In the designed concepts, a search for harmony with the space was pursued through designs that evoke the past and create contrast, due to both the constraints of the target region and the futuristic nature of the product group. Since other competitors in the market are also generally producing futuristic products, it was thought that organic forms would increase preferability due to the contrast they create, and designs of this type were realized. The concept development phase was completed through designs with soft lines that will serve as a bridge between the old and the new.

4.2. House of Quality and Concept Selection

The five designed concepts must be selected based on the established criteria. Within this scope, the House of Quality methodology was applied. The technical parameters determined to establish the relationships between the concepts and the desired work compatibility are, respectively: use of recycled or renewable materials, long-lasting use, repairability, recyclability, less material usage through minimal design, modularity, and compatibility with electronic components. Each parameter was given an importance rating. The importance ratings of the parameters, in the specified order, are: 15, 10, 10, 10, 20, 20, 15. All these parameters were scored by the company with which the industrial collaboration is established, from concept 1 to 5, and industrial applicability was taken as the basis of the scoring.

Table 4.3. House of Quality Methodology and Concept Scoring Results

Technical Parameters	Importance Rating	Concept -1	Concept -2	Concept -3	Concept -4	Concept -5
Use of recycled or renewable materials.	**15**	12	10	12	13	11
Long-lasting use.	**10**	7	5	7	7	7
Repairability.	**10**	7	6	8	8	7
Recyclability.	**10**	8	6	8	8	6
Less material usage through minimal design.	**20**	16	12	15	18	13
Modularity.	**20**	16	15	18	18	15
Compatibility with electronic components.	**15**	13	13	13	14	12
Absolute Importance		**1235**	**1055**	**1265**	**1355**	**1105**
Relative Importance (%)		**20.532**	**17.539**	**21.030**	**22.527**	**18.370**

Looking at the scores given in Table 4.3, the absolute importance and relative importance (%) values of the concepts are seen. Absolute importance refers to the total scores of the concepts, while relative importance refers to their percentage importance among all concepts. Under these conditions, it is seen that the concept to be selected is concept 4. It is understood that this concept stands out compared to the others in terms of less material use through minimal design, inclusion of modularity features, compatibility with electronic parts, and the use of recycled materials.

Within the scope of the concept studies carried out, it was understood that concept 4 should be selected. However, before proceeding to the engineering design phase of the concept, revisions, if any, need to be made, and the industrial design needs to be completed. In this intermediate phase, improvements were made to the design form of concept 4 based on discussions. Based on the idea that the front surface seen in Figure 4.4 was too empty and that the electronic lighting inside the device should also affect the user, different patterns were designed for the front surface of the design. Thus, it was intended to add a dynamic structure to the user through colors and an interactive structure through the designed patterns. In line with the requests of the company within the industrial collaboration, the pattern design presented at the beginning was chosen from among the designed patterns.

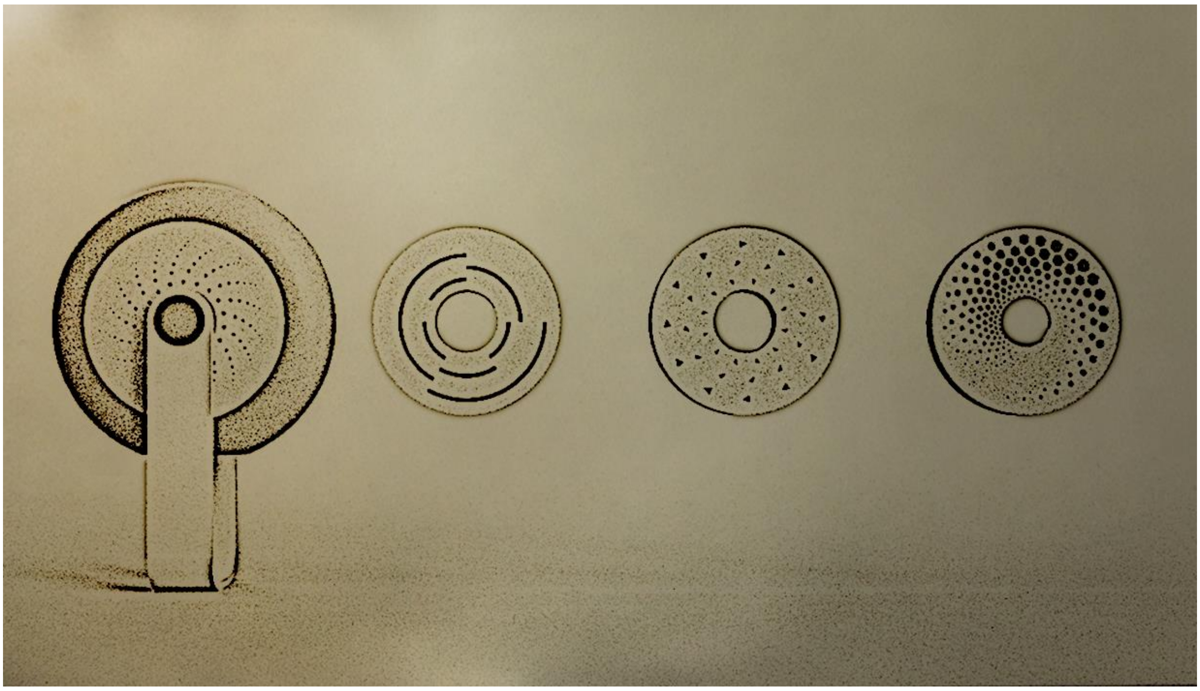


Figure 4.6. Front Surface Pattern Designs of Concept-4

The mentioned pattern designs for Concept 4 are given in Figure 4.6. The company's use of initiative at this point has created a situation that also emphasizes the importance of the company worked with in industrial product design processes. Parameters such as the knowledge, experience, and quality of companies have shown that, in addition to standardized design processes, in processes where initiative is taken, the quality of the product can be raised or lowered. At this point, in line with the requested revision, the design has become more dynamic and impressive, and the opinion that the use of the first and fourth patterns would be appropriate was advocated. However, due to cost considerations, the first pattern was chosen, and the form was finalized in the industrial design.

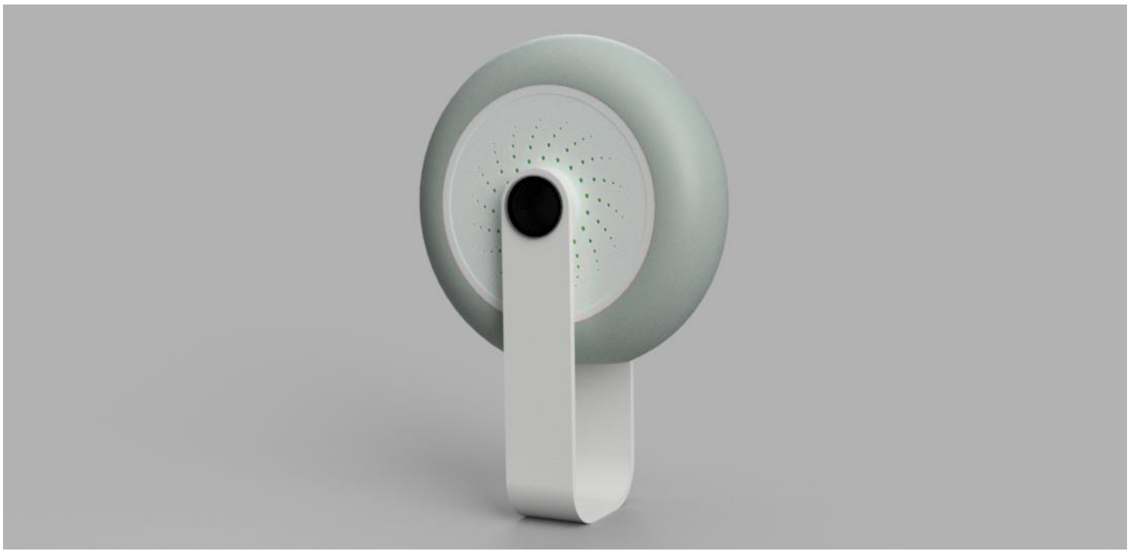


Figure 4.7. Final Version of CAD for Concept-4

The completed industrial design form of Concept 4 is given in Figure 4.7. This is presented as an image where the CAD (computer-aided design) is complete and the colors are defined. After this point, the study will proceed with the material selection and engineering design processes, and then the case study will be completed with the production of a scaled model (1:1) as the final step of the sustainable design application.

4.3. Creating Material Options

Materials constitute one of the most important aspects of sustainable design. The material to be used in the designed product becomes the main source of millions of tons of emissions with mass production. In this context, one of the most important features of the developed Concept 4 is that it includes natural material in a way that does not create problems in terms of product safety and aesthetics. Not only thermoplastic material was used in the product design, but wood material was used in the part where factors such as electrical insulation of electronic parts are not present. This situation has significantly reduced the use of thermoplastics and, consequently, emissions.

With the engineering design, assembly holes and strength-increasing sections of the parts were defined in the product. Thus, it was seen that there are three basic parts that make up the product. These were; the male and female parts, and the arm part.

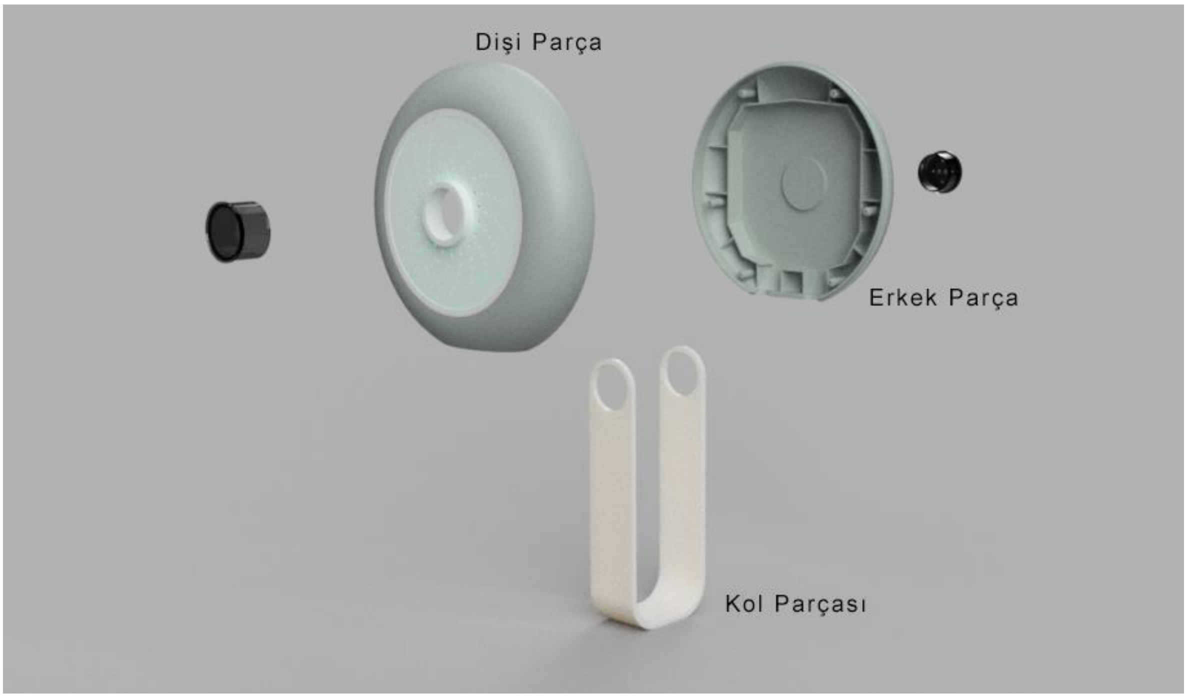


Figure 4.8. Engineering Design and Exploded Perspective View for Concept -4

According to the parts shown in Figure 4.8, the volume value for the arm part is 481.052 cm^3, the volume value for the female part is 626.387 cm^3, and the volume value for the male part is 589.082 cm^3. Due to the arm part being entirely made of wood, it is observed that an average emission reduction of one-third is achieved in this step compared to competing products.

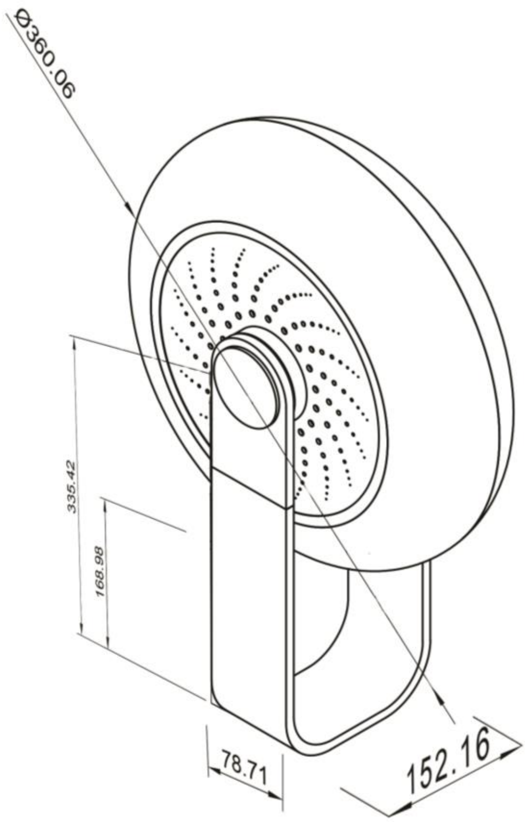


Figure 4.9. Millimetric General Dimensions for Concept -4

Along with the mentioned volume data, the overall dimension values given in Figure 4.9 indicate where the volume is concentrated. However, when values are calculated using the planned material data, the density value also changes accordingly, making it difficult to determine the source of mass increases before material selection. When the material selection for the arm part is applied as wood, according to the Autodesk Fusion 360 material library, the density is 0.570 g/cm³, and the emission value is taken as 0, due to the material being renewable and biodegradable in nature. However, these values will vary depending on mass production and the conditions of the supplied forest. Under these conditions, the mass of the arm part is:

$$Arm\ Part\ Mass\ (gr) = 0.570 \frac{gr}{cm^3}\ x\ 481.052\ cm^3 \quad (4.1)$$

As shown in Equation 4.1, it takes the value of 274.199 grams.

For the material to be defined for the male and female body parts, material options that can be selected by applying the Rule of Mixtures methodology with 10% variations of ABS and PC materials, and the values of the mechanical and thermal properties of these material mixtures were determined. Mixture calculations were carried out based on the values that the methodology will approximately provide: density, tensile strength, yield strength, Young's modulus, price, and greenhouse gas emissions. According to the material data of the ANSYS company given in Table 3.3, the mixture values were calculated as stated in Table 4.4.

Table 4.4. Material Properties of ABS/PC Mixtures: Values According to the Rule of Mixture

Mixing Proportions (100%)	**Density (gr/cm^3)**	**Tensile Strength (MPa)**	**Yield Strength (MPa)**	**Young's Modulus (GPa)**	**Price (USD/Kg)**	**GHG (kg CO_2)**
ABS:100 + PC:0	1.1	41.5	35	2	2.55	3.8
ABS:90 + PC:10	1.105	43.95	37.95	2.02	2.78	4.025
ABS: 80 + PC:20	1.11	46.4	40.9	2.04	3.01	4.25
ABS:70 + PC:30	1.115	48.85	43.85	2.06	3.24	4.475
ABS:60 + PC:40	1.12	51.3	46.8	2.08	3.47	4.7
ABS:50 + PC:50	1.125	53.75	49.75	2.1	3.7	4.925
ABS:40 + PC:60	1.13	56.2	52.7	2.12	3.93	5.15
ABS:30 + PC:70	1.135	58.65	55.65	2.14	4.16	5.375
ABS:20 + PC:80	1.14	61.1	58.6	2.16	4.39	5.60
ABS: 10 + PC:90	1.145	63.55	61.55	2.18	4.62	5.825
ABS:0 + PC:100	1.15	66	64.5	2.2	4.85	6.05

The basic mechanical and thermal properties of the material that will result from mixing ABS and PC materials in increments of 10 percentage points have been calculated, and these values are given in Table 4.4. These mixtures will be applied to the male and female parts.

4.4. Material Definition and Part Analysis

The fact that the male and female parts forming the body component are made of thermoplastic material has become a constraint due to the electronic components inside and global standards. Under these conditions, separate analyses were carried out for the male and female parts in order to select the ABS and PC mixture to be used. First, in the static stress analysis to be opened via Autodesk Fusion 360 software, the male and female parts were loaded separately, and material definitions were provided for the 11 mixtures specified in Table 4.4, and the analyses were started. Each analysis was performed at a room temperature of 25°C, with a total force of 1000N applied from the directions indicated in Figure 3.2.

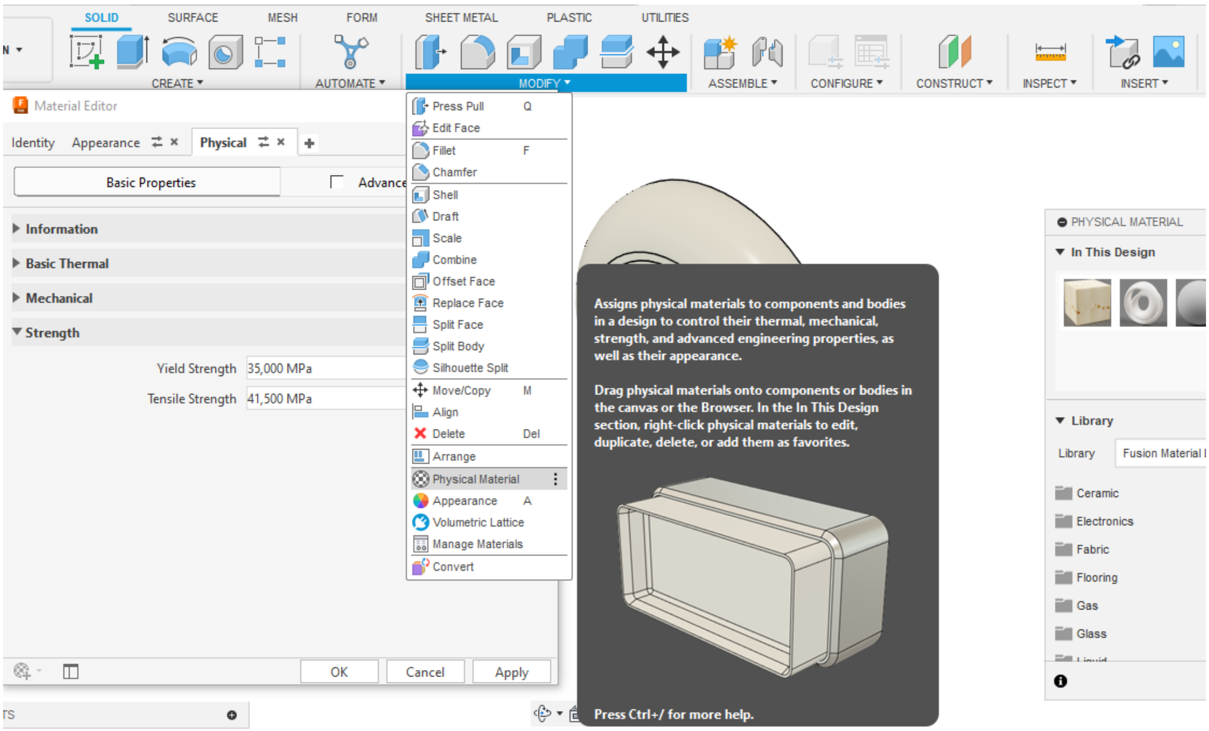


Figure 4.10. Material Definition via Autodesk Fusion360 Software

Before performing a static stress analysis via Autodesk Fusion 360 software, it is first necessary to define the material. As shown in Figure 4.10, when the "Physical Material" section is clicked, the "Physical Material" section that appears on the right is opened. The material definition process is performed by dragging and dropping the selected material onto the part. If a different material needs to be defined, right-click on the material, select the "edit" option, and the material values can be entered manually via the Material Editor that opens on the left. Also, a new name can be given to the material. As seen in Figure 4.10, the ABS material data from ANSYS company has been manually defined in Autodesk Fusion 360 software.

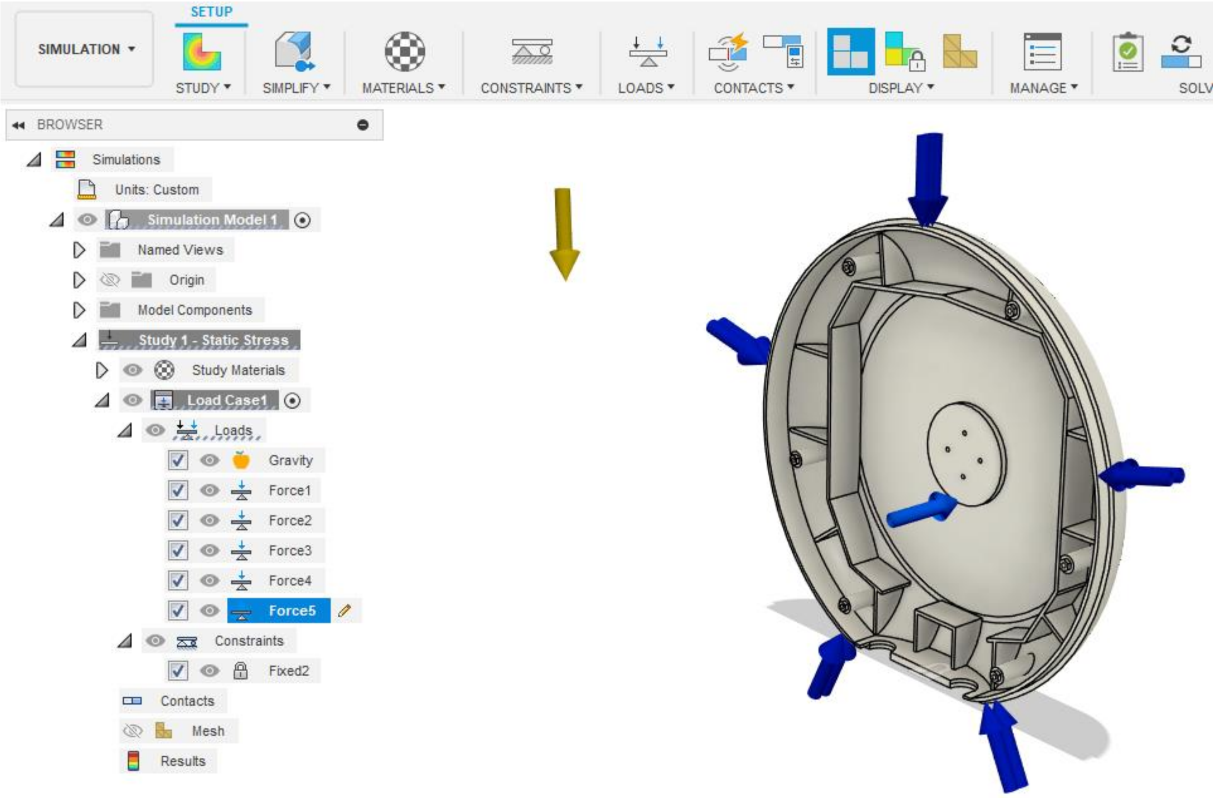


Figure 4.11. Defining Forces via Autodesk Fusion360 Software

During the definitions, force was applied along 6 axes, and no force was applied from the point where the product is connected to the ground. The force directions in the calculations including gravity are shown in Figure 4.11 for the male part. While it is possible to fix the product from its rear side, fixation from this point was not considered. Fixations made from this point would cover a larger surface area, resulting in analysis results with higher strength. Therefore, in order to see the fractures more clearly and to have high analysis sensitivity, the analyses were performed based on fixing from the bottom point.

Safety factor values are an important basis for material selection in static stress analysis. Safety factor values between 1-3 indicate that the situation is critical and the probability of breakage is high, while values of 1 and below definitely indicate that the product will break. Values between 3-6 emphasize that the product has ideal strength, while values of 6 and above indicate that the product is overly good, and suggestions such as reducing the quality of materials and cheapening the design should be considered to reduce costs. Under these conditions, the safety factors resulting from the static stress analyses performed separately for the male and female parts are given in Table 4.5 for the male part and in Table 4.6 for the female part.

Table 4.5. Safety Factor Values for Male Part According to Mixtures

	Density (gr/cm^3)	Part Mass (gr)	Tensile Strength (MPa)	Yield Strength (MPa)	Price (USD/Kg)	GHG (kg CO_2)	Min. Safety Factor
ABS:100 + PC:0	1.1	647.99	41.5	35	2.55	3.8	**1.80**
ABS:90 + PC:10	1.105	650.936	43.95	37.95	2.78	4.025	**1.948**
ABS: 80 + PC:20	1.11	653.881	46.4	40.9	3.01	4.25	**2.10**
ABS:70 + PC:30	1.115	656.826	48.85	43.85	3.24	4.475	**2.251**
ABS:60 + PC:40	1.12	659.772	51.3	46.8	3.47	4.7	**2.40**
ABS:50 + PC:50	1.125	662.719	53.75	49.75	3.7	4.925	**2.554**
ABS:40 + PC:60	1.13	665.663	56.2	52.7	3.93	5.15	**2.705**
ABS:30 + PC:70	1.135	668.608	58.65	55.65	4.16	5.375	**2.857**
ABS:20 + PC:80	1.14	671.553	61.1	58.6	4.39	5.60	**3.01**
ABS: 10 + PC:90	1.145	674.499	63.55	61.55	4.62	5.825	**3.16**
ABS:0 + PC:100	1.15	677.444	66	64.5	4.85	6.05	**3.31**

As seen in Table 4.5, when the Rule of Mixtures methodology was applied, different mechanical and thermal properties were calculated for each mixture proportions, and static stress analyses were performed under the specified conditions for each mixture proportions, resulting in safety factor results and part mass according to this material. Considering the safety factor values, values between 2.5 and 3 were named as acceptable due to necessity, and mixtures with a value of 3 and above were expressed as optimal. The mixture of 20% ABS and 80% PC gave optimal results for both parts, indicating its preferability in terms of price/performance.

Table 4.6. Safety Factor Values for Female Part According to Mixtures

	Density (gr/cm^3)	Part Mass (gr)	Tensile Strength (MPa)	Yield Strength (MPa)	Price (USD/Kg)	GHG (kg CO_2)	Min. Safety Factor
ABS:100 + PC:0	1.1	876.38	41.5	35	2.55	3.8	**1.84**
ABS:90 + PC:10	1.105	880.665	43.95	37.95	2.78	4.025	**1.998**
ABS: 80 + PC:20	1.11	884.65	46.4	40.9	3.01	4.25	**2.154**
ABS:70 + PC:30	1.115	888.635	48.85	43.85	3.24	4.475	**2.309**
ABS:60 + PC:40	1.12	892.62	51.3	46.8	3.47	4.7	**2.464**
ABS:50 + PC:50	1.125	896.604	53.75	49.75	3.7	4.925	**2.62**
ABS:40 + PC:60	1.13	900.589	56.2	52.7	3.93	5.15	**2.775**
ABS:30 + PC:70	1.135	904.574	58.65	55.65	4.16	5.375	**2.93**
ABS:20 + PC:80	1.14	908.559	61.1	58.6	4.39	5.60	**3.09**
ABS: 10 + PC:90	1.145	912.544	63.55	61.55	4.62	5.825	**3.24**
ABS:0 + PC:100	1.15	916.529	66	64.5	4.85	6.05	**3.397**

As seen in Table 4.6, the mixture with the most economical and optimal strength value was 20% ABS and 80% PC. While the carbon emission value is very high when it is entirely PC, the 20% ABS and 80% PC mixture is preferred in terms of price criteria. At this point, for designs that will be subject to different conditions, for example, if a minimum yield strength of 60 MPa is required, more elimination criteria can be applied through the table, thus making material selections more effective in terms of both sustainability and price/performance with the specified method. With the creation of these tables, it has been successfully revealed which material will be selected after the analysis results.

4.5. Material Selection and Physical Model Production

The safety factor values resulting from the static stress analyses showed that the 20% ABS and 80% PC mixture is optimal for both thermoplastic body parts. Under these conditions, the total mass of the two parts is calculated as shown in Equation 4.2:

$$\sum Body\ Mass\ (gr) = 908.559 + 671.553 \tag{4.2}$$

taking the value of 1580.112 grams. Therefore, when the price calculation is made based on the mass value:

$$Total\ (USD) = 1.580\ kg\ x\ 4.39\ USD\ (per\ kg) \tag{4.3}$$

the calculation is performed as given in Equation 4.3, and it is seen that there is a thermoplastic material usage of 6.93 USD per product. In addition, for the carbon emission data to be calculated based on the product mass:

$$\sum Carbon\ (kg) = 1.580\ kg\ x\ 5.60\ kg\ CO_2 \tag{4.4}$$

the calculation shown in Equation 4.4 is applied, and an emission value of 8.848 kg CO_2 is obtained. Since these calculations are made based on the product mass, material losses due to the production method and other greenhouse gases calculated in terms of CO_2 emission equivalents are not included. Emissions from mass production, supply chain, and paint-related emissions are not within the scope of the study. These calculations represent example steps for how a product prepared for mass production can be developed sustainably by performing basic calculations.

Thanks to the wooden arm part;

$$\sum ArmPart\ (gr)\ = 481.052\ cm^3\ x\ 1.14\ gr/cm^3 \tag{4.5}$$

As seen in equation 4.5, the mass of the thermoplastic part was not revealed and the production of an extra thermoplastic part with a mass of 548.399 grams was avoided. In this way;

$$\sum Carbon.ArmPart\ (kg) = 0.548\ kg\ x\ 5.60\ kg\ CO_2 \tag{4.6}$$

It was avoided to cause 3.06 kg of carbon emissions as a result of the calculations in equation 4.6.

As a result of the electric vehicle charging station design with 20% ABS and 80% PC material defined, the mass of the product is composed of; 1580.112 grams of body thermoplastic parts, 275 grams of arm part, 1798 grams of main electronic parts, 55 grams of polycarbonate parts protecting the main electronics, 355 grams of electrical connection cable, and 2000 grams of type 2 charging connection cable. The total expected product mass was 6063.112 grams. Under these conditions, material definitions were made for the physical and 1:1 scale model to be produced.

Figure 4.12. Front View of the Produced Model

The designed product achieved the total product mass with a 5% deviation due to internal insulation parts and bolts. Figure 4.12 shows a front view image of the assembled Concept 4 model with internal electronic components. At this point, the easy assembly of the product has attracted attention, and as stated in the House of Quality criteria, easy repairability has been ensured thanks to the modular structure, and the product has included long-lasting use features by being renewed instead of being discarded thanks to the easy replacement of parts. With its minimalist and soft lines that use materials efficiently and sparingly, it has been seen that various advantages have been achieved in terms of material emissions. In this product, where carbon emissions were avoided by one-third, both based on the overall product mass and by using wood material, compliance with sustainable design principles has been demonstrated in the design. With different color options, the wooden part also has options that can attract the attention of users with wood color and texture instead of white color.

Figure 4.13. Side View of the Produced Model

The visual of the side view of the produced concept-4 model in terms of wall thickness is given in Figure 4.13.

Figure 4.14. Perspective View of the Produced Model

The perspective visual of the final version of the AC 22 kW electric vehicle charging station, designed with sustainable design principles, is given in Figure 4.14.

Table 4.7. Key Feature Comparison for Designed Product and Competitive Products

Products/Parameters	Compatibility with Usage Location	Modularity	Repairability	Body Material	Product Mass (Incl. Cable)
Schneider Charge	Compatible with commercial locations due to its corporate appearance.	Same body design for all capacities up to 22 kW.	Body design suitable for repair.	Thermo-plastic	5.2 kg
Keba KeContact P30 C Series	Compatible with modern architecture, residential charging station.	Same body design for all capacities up to 22 kW.	Body design suitable for repair.	Thermo-plastic	7.8 kg
Tesla Home Charging	Suitable for many modern and historical buildings with its minimalist and modern design.	Same body design for all capacities up to 11.5 kW.	Body design suitable for repair.	Thermo-plastic	5.7 kg
Produced Model (Concept-4)	Compatible with German traditional architecture, with a simple and minimal design, suitable for both rural and urban environments.	Same body design for all capacities up to 22 kW.	Body design suitable for repair.	Thermo-plastic and Wood	6.06 kg

Table 4.7 presents comparisons between the designed concept and competing products. Similar technical specifications are present in all products, and the use of thermoplastics indicates the products' suitability for recycling. The mass of the designed product, including the wooden part, being at an average level puts it ahead of the others in terms of emissions. It is seen that the point where the designed product should differentiate itself is its compatibility with the place of use and the use of recyclable and renewable materials. It is necessary not to fall behind the competitors in technical parameters such as long-lasting use, repairability, and modularity.

5. CONCLUSIONS

The industrial product design study, in which sustainable design principles were applied, has been completed as a case study. It has been clearly seen that the study, from the introductory phase to the conclusion, is within the focus of industrial organizations that will develop products for the industry and disciplines involved in product development processes. The product produced at the end of the study was prepared as the first prototype version of the product, and it is planned to be made ready for mass production with design revisions as a result of field feedback. Within the framework of the studies carried out, it was found that knowing what the sustainable design strategies in the literature are is very important in terms of target market scope and impact. The sustainable design strategies examined within the scope of the study were analyzed in terms of their impact and scope, and in this direction, a sustainable design strategy was selected and correct progress was ensured. Since the understanding of sustainability is different in all strategies, the importance of choosing a strategy for the market in which the product will enter was seen. Otherwise, the desired results cannot be achieved, and time and labor will be lost. Since the target market in the study is Germany, the most suitable sustainable design strategy in terms of impact and scope was selected as EU Ecodesign. It was seen that the design should include certain features in terms of material and product dimensions according to the features included in the selected design strategy. In terms of material; it was understood that parameters such as focusing on the use of natural materials, avoiding toxic/poisonous materials, choosing renewable materials, choosing recyclable materials, and choosing recycled materials should be followed. In terms of product; it was understood that it should include features such as long-lasting use, repairability, modular structure for internal parts, and material efficiency. Thus, primary design constraints were revealed according to the chosen sustainable design strategy.

The process was carried out in collaboration between academia and industry, in direct alignment with industrial product design stages, so that the results could be realistic both for the market and the literature. Within this scope, the design thinking methodology was applied, taking into account the design constraints obtained from the design strategy and the constraints of the company that will support production and R&D activities. In this way, concept designs suitable for the target market were realized. The House of Quality methodology was applied, the concept designs were scored according to the constraints of the collaborating company, and the most suitable design was selected, completing the industrial design activity. In order to increase the proportion of renewable and recyclable materials in the product and to determine the optimum for the body parts using the Rule of Mixtures methodology, the parts that would not disrupt the electrical insulation in the design were specifically examined. In this context, the body part where the main electronic parts are located and the arm part where the cables will be held were separated in terms of material. Within the scope of renewable and recyclable materials, it was decided to make the arm part from wood obtained from pine trees, and for the male and female parts forming the body, the Rule of Mixtures methodology was applied, and a choice was made between ABS and PC, which are standardized materials in this field. The material mixtures determined by the Rule of Mixtures methodology were subjected to static stress analyses, and the mixture that gave the best price/performance values for the male and female parts and, in this context, caused the most suitable carbon emission was determined. Under these conditions; it was seen that a material mixture of 20% ABS and 80% PC should be selected for the male and female parts. These parts constituted a total mass value of 1580.112 grams. If the arm part to be made of pine wood had been produced with this same thermoplastic mixture, the mass value would have been 548.399 grams, and it would have caused 3.06 kg of carbon emissions in terms of raw material carbon emissions. Since the 1580.112 grams of body parts have a raw material carbon emission of 8.848 kg, an additional 3.06 kg of emissions was avoided with the sustainable design strategy. This situation created an emission reduction of approximately 25% during the product design phase. The total mass of the product, assembled with the charging cable, internal electronic parts, and power cable, was 6063.112 grams.

The following answers were found to the questions determined in the target of the study, together with the information obtained in the findings and results section:

1. For the implementation of sustainable design, sustainable design strategies should be examined in terms of impact and market, the strategy suitable for the product objective should be selected, and the design features included in the strategy should be taken as design constraints. Then, concepts should be created with methodologies such as design thinking. For products where the Rule of Mixtures methodology can be applied during the material selection phase, tables including emission values should be created according to mixture proportions. The design process should be completed by making a selection based on parameters such as price/performance and emissions, using the safety factor values from static stress analyses.

2. For optimum material selection, materials that can be mixed are mixed according to the Rule of Mixtures methodology, and new material and properties are tabulated. Material emissions are applied within the scope of the Rule of Mixtures, improving the table content. Safety factor values are revealed for the parts, and eliminations are made according to the desired parameter. The selection can be made based on emissions or another parameter to be highlighted.
3. The sustainable design strategy has direct control over the product emission value. Criteria that will occur during the design phase, such as minimal designs that will use less material and the preferability of natural materials, directly affect the product emission.
4. It has been seen that less harm will be done to nature due to the reduction of carbon emissions with the correct application of strategies in sustainable design. As can be understood from the study, product emissions decreased by approximately 25% only through design processes.
5. It has been seen that sustainable design affects the manufacturer's economic situation in various ways. High-quality and long-lasting products have brought high costs. Similarly, the use of natural materials has also increased the need for reinforcing materials, creating negative effects on cost. However, factors such as minimalist designs directly reduce the material to be used, thus creating a positive effect on the manufacturer's economy. Therefore, it has been seen that sustainable design can have positive and negative effects on the manufacturer in terms of cost, depending on the product group and the chosen design strategy.

The conducted case study included various methodologies such as sustainable design strategy selection, design thinking methodology application, concept selection with the House of Quality methodology, determination of material options with the Rule of Mixtures methodology, and comparison of safety factors of different material mixtures through static stress analysis, and it has been a guiding study. It is believed that similar studies will contribute to the development of the industry and the literature in these times when sustainable product development studies are increasing in Türkiye and globally.

The case study shows that it is possible to reduce carbon emissions from the perspectives of nature, science, and industry. However, it should not be overlooked that the study was conducted only for emission reduction in terms of industrial product design. All stages and stakeholders of the product life cycle, such as the efficiency and emissions of the production facilities where the product will be manufactured, the emissions that will be created by material and other suppliers, the facilities where the product will be recycled after use or the products that will be produced by recycling, and what will be done after the product's life, must work in an interdisciplinary, transparent, coordinated, and comprehensive manner for a sustainable product.

6. RECOMMENDATIONS

With this thesis work, recommendations have been developed for the scientific and industrial worlds. From the perspective of the scientific world, it is recommended that:

- It has been seen that applied studies in the field of sustainability should be carried out in an interdisciplinary manner, and studies in this field, such as theses and research articles, should be carried out together with students from different disciplines and in cooperation with industry.
- It has been seen that each discipline has room for maneuver within itself within the scope of sustainability (such as sustainability in design, production, transportation, economy, education, health, etc.), and therefore, disciplines should also develop within themselves.
- Sustainable product design strategies suitable for Türkiye's conditions should be developed.
- Scientific studies should be carried out in coordination and collaboration with countries that transparently calculate and share emission data.

From the perspective of industry, it is recommended that:

- In terms of emissions, the focus should not only be on topics such as energy, chemistry, and material technologies; it should be remembered that physical products are used in all sectors (from analysis to production) and that these physical products go through a design process, and if the same weight is given to sustainable design, emissions will indirectly decrease.
- Different approaches should be followed by working closely with the scientific world and conducting international studies.
- The importance of correctly determining sustainable product design strategies for the target product and market, and the correct analysis of the financial losses that will result otherwise.
- Companies should establish effective and efficient sustainability practices across all internal processes. Crucially, this includes designing products so that components that may become waste or malfunction can be easily recycled or repurposed into new products, potentially across different production lines.
- Calculations in cases where sustainability data are not transparent and reliable will not go beyond saving the day; creating a corporate culture in this direction will be effective for the global market.

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APPENDIX

APPENDIX-1: DECLARATION OF COOPERATION

KOOPERATIONSSCHREIBEN

Frankfurt, 30.12.2024

Sehr geehrte Damen und Herren,

Betreff: Masterarbeit mit dem Titel „EXAMPLE APPLICATION IN SUSTAINABLE INDUSTRIAL PRODUCT DESIGN: 22 kW AC ELECTRIC VEHICLE CHARGING STATION“

Als Unternehmen Rudis Forschung & Entwicklung GmbH mit Sitz in Frankfurt, Deutschland, haben wir die Masterarbeit mit dem Titel „EXAMPLE APPLICATION IN SUSTAINABLE INDUSTRIAL PRODUCT DESIGN: 22 kW AC ELECTRIC VEHICLE CHARGING STATION“ unterstützt. Die Masterarbeit wurde im Rahmen des Masterprogramms für Industrielle Nachhaltigkeit an der Bilecik Şeyh Edebali Universität in der Türkei von Mustafa CANBULAT unter der Betreuung von Prof. Dr. Ahmet Fevzi SAVAŞ entwickelt. Unsere Unterstützung erfolgte von Februar 2024 bis Januar 2025 und umfasste technische Ausstattungen, elektronische Bauteile sowie technische Informationen.

Wir hoffen, auch in Zukunft solche internationalen Kooperationen und erfolgreiche Ergebnisse erzielen zu können.

Mit freundlichen Grüßen,

OZGUR YILMAZ

Geschäftsentwicklung Manager

Rudis Forschung & Entwicklung GmbH