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DEVELOPMENT OF GREEN PRODUCT DESIGN

Thesis Submitted
in Partial Fulfillment of the Requirements for the
Degree of

DOCTOR OF PHILOSOPHY

in

Design

by

Mohd Tayyab
(Roll No: 2K19/PHDDES/05)

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December, 2024

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This thesis would not have been possible without the collective support, encouragement, and contributions of all these individuals. To all of you, I offer my heartfelt thanks.

Mohd Tayyab

CANDIDATE'S DECLARATION

I **Mohd Tayyab** hereby certify that the work which is being presented in the thesis entitled **Development of Green Product Design** in partial fulfillment of the requirements for the award of the Degree of Doctor of Philosophy, submitted in the **Department of Design, Delhi Technological University** is an authentic record of my own work carried out during the period of **August, 2019 to October, 2024** under the supervision of **Prof. Ranganath M. Singari** and **Prof. Peer M. Sathikh.**

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Certified that **Mohd Tayyab** (2K19/PHDDES/05) has carried out their research work presented in this thesis entitled **"Development of Green Product Design"** for the award of **Doctor of Philosophy** from the Department of Design, Delhi Technological University, Delhi, under our supervision. The thesis embodies results of original work, and studies are carried by the student himself, and the contents of the thesis do not from the basis for the award of any other degree to the candidate or to anybody else from this or any other University/Institution.

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DEVELOPMENT OF GREEN PRODUCT DESIGN

MOHD TAYYAB

ABSTRACT:

Environmental degradation and climate change have increasingly brought sustainability to the forefront of global challenges, especially within industrial and product design practices. The need to balance functionality, affordability, and environmental responsibility has created an urgent demand for innovative frameworks that enable the creation of green products. This thesis addresses this critical research gap by developing a framework for green product design, aimed at facilitating sustainability across the product lifecycle while maintaining practicality for diverse industrial applications. This research sets out to achieve four primary objectives: to explore the role of recycled and green materials in sustainable product design, to study the significance of flexibility, control, and sensitivity in managing green constraints during the initial stages of the product lifecycle, to conceptualize and develop a comprehensive framework for green product design, and to validate the framework through real-world case studies.

The research problem centers on the inadequacies of existing tools and frameworks for green product design. Conventional approaches, such as full Life Cycle Assessment (LCA), are often resource-intensive, requiring significant technical expertise, financial investment, and time. As a result, these methods are challenging to implement, particularly for small and medium-sized enterprises. Moreover, the integration of recycled and green materials, though recognized as essential, lacks a structured approach to evaluate their feasibility and effectiveness. Furthermore, most available frameworks fail to address the entire product lifecycle cohesively or lack a mechanism for prioritizing key environmental parameters. These limitations create a significant barrier to achieving a systematic, practical, and adaptable green product design process.

To overcome these challenges, this study adopted a methodological approach that integrates systematic literature review, decision-making techniques, and lifecycle assessment tools. A systematic literature review was conducted following PRISMA guidelines to identify gaps, trends, and critical attributes of green product design. By leveraging state-of-the-art tools and databases, the review provided a comprehensive understanding of the theoretical underpinnings and practical challenges in the field. The development of the framework was guided by the insights derived from the review and involved categorizing green design considerations into three primary lifecycle phases: manufacturing, use, and end-of-life. Each phase incorporates a set of attributes designed to optimize sustainability outcomes, selected through a decision-making process that involved consultations with industry experts and academic researchers.

To enhance its practical applicability, the framework employs a simplified, single-figure Life Cycle Assessment (LCA) methodology. This approach utilizes carbon emissions data sourced from the OKALA Practitioner Guide, providing a streamlined yet reliable method for assessing environmental impact. Unlike traditional LCA methods, which often present challenges due to their complexity, this single-figure LCA offers an accessible solution for evaluating sustainability metrics without compromising accuracy. The proposed framework's adaptability is further enhanced through sensitivity analysis and flexibility measures, enabling its use across a wide range of industries and product types.

The validation of the framework was conducted through two case studies: a bicycle and a household appliance. These case studies were selected to represent diverse product categories, enabling the evaluation of the framework's effectiveness in addressing varying design and lifecycle considerations. For both cases, the results obtained using the proposed framework were benchmarked against those derived from existing LCA software. The findings demonstrated a high degree of accuracy and consistency, confirming the framework's reliability and applicability. Furthermore, the simplified approach proved advantageous in reducing the time and resource requirements typically associated with conventional LCA methods.

The key findings of this research highlight the transformative potential of integrating recycled and green materials into product design. For instance, the use of recycled materials in the case studies significantly reduced carbon emissions without compromising product quality or cost efficiency. This underscores the importance of material selection as a cornerstone of sustainable design. Additionally, the study revealed the critical role of early-stage flexibility in addressing green constraints, such as regulatory compliance, energy efficiency, and waste minimization. By incorporating flexibility and sensitivity measures, the framework ensures that manufacturers can adapt to evolving environmental requirements and consumer demands.

The implications of this research extend beyond academia to industry and policymaking. For industries, the proposed framework offers a practical tool for implementing sustainable practices without requiring extensive technical expertise. Its simplicity and adaptability make it particularly valuable for small and medium-sized enterprises, which often face resource constraints in adopting green design principles. For policymakers, the framework provides a structured basis for developing guidelines and standards that promote sustainability across sectors. By emphasizing lifecycle integration and carbon footprint reduction, the framework aligns with the goals of the circular economy and can support initiatives aimed at reducing environmental impact on a broader scale.

Despite its contributions, this study acknowledges certain limitations. The framework's validation through two case studies, while effective, limits its generalizability across all industries. The reliance on OKALA data for carbon emissions values may also restrict its applicability in regions or contexts where more detailed or localized data is required. Additionally, the framework has yet to be tested over extended product lifecycles or with more complex product systems. These limitations provide avenues for future research to build upon the findings of this study.

Future research can explore several promising directions. First, expanding the validation process to include a wider range of industries and product categories would enhance the framework's robustness and applicability. Second, integrating advanced sustainability metrics, such as water and energy footprints, alongside carbon emissions, would provide a more comprehensive assessment of environmental impact. Third, the development of a digital tool or software based on the framework could further simplify its implementation and increase accessibility for non-technical stakeholders. Finally, long-term pilot testing in collaboration with industries would provide valuable insights into the framework's performance in real-world production environments.

In conclusion, this thesis represents a significant advancement in the field of green product design by addressing critical gaps in existing methodologies and offering a practical, lifecycle-oriented framework. The integration of recycled materials, the emphasis on early-stage flexibility, and the adoption of a simplified LCA method collectively ensure that the framework is both effective and accessible. The findings not only contribute to the academic discourse on sustainable design but also hold tangible implications for industries and policymakers striving to reduce environmental impact. By bridging the gap between theory and practice, this research paves the way for a more sustainable approach to product development, fostering innovation and responsibility in equal measure.

List of Publications:

Journal Publication:

1) Mohd Tayyab, Ranganath M. Singari, and Peer M. Sathikh. "Evaluating the Environmental Impact of a Bicycle: A Life Cycle Assessment with a New Green Product Design Framework." Educational Administration: Theory and Practice, SCOPUS/ESCI, Published, DOI: 10.53555/kuey.v30i5.3539.

2) Mohd Tayyab, Ranganath M. Singari, and Peer M. Sathikh. "Evaluating the Environmental Impact of a Home Appliances: A Life Cycle Assessment with a New Green Product Design Framework." Educational Administration: Theory and Practice, SCOPUS/ESCI, Published, DOI: 10.53555/kuey.v30i5.5674.

3) Mohd Tayyab, Ranganath M. Singari, and Peer M. Sathikh. " Comparative Analysis of Carbon Footprint and Environmental Impact of Laptops" Nanotechnology Perceptions, SCOPUS, Published, DOI: https://doi.org/10.62441/nano-ntp.vi.3217.

4) Mohd Tayyab, Shadab Ahmad, Md Jamil Akhtar, Peer M. Sathikh, and Ranganath M. Singari. "Prediction of Mechanical Properties for Acrylonitrile-Butadiene-Styrene Parts Manufactured by Fused Deposition Modelling Using Artificial Neural Network and Genetic Algorithm." International Journal of Computer Integrated Manufacturing, SCI, Published, DOI: 10.1080/0951192X.2022.2104462.

Conference Presentations:

5) Mohd Tayyab, Ranganath M. Singari, and Peer M. Sathikh. "Understanding the Interplay of Flexibility, Control & Sensitivity Towards Green Constraints in Product Design: A Review." International Conference of Advance Research and Innovation (ICARI-2024), Organized by International Journal of Advance Research and Innovation (Google Scholar), 28th January 2024, Delhi State Centre, Institution of Engineers (Engineers Bhawan), New Delhi.

6) Mohd Tayyab, Ranganath M. Singari, and Peer M. Sathikh. "Design for Impact: A Framework for Green Product Design." International Conference of Advance Research and Innovation (ICARI-2024), Organized by International Journal of Advance Research and Innovation (Google Scholar), 28th January 2024, Delhi State Centre, Institution of Engineers (Engineers Bhawan), New Delhi.

7) Mohd Tayyab, Ranganath M. Singari, and Peer M. Sathikh. Study of Green Materials and Processes for Development of Green Product Design. International Conference of Design and Materials (ICDM-2023), Organized by NIT Delhi, July 2023, NIT Delhi, New Delhi.

CONTENTS

LIST OF TABLES:

LIST OF FIGURES:

CHAPTER 1:

INTRODUCTION

In the face of escalating environmental challenges, the imperative for sustainable practices has become increasingly pronounced. The late 20th century witnessed a burgeoning awareness of the profound impact of industrial growth on our planet, prompting a paradigm shift towards more eco-conscious approaches (Pina et al., 2015). In this context, the concept of Green Product Design (GPD) emerged as a beacon of hope, offering a strategic pathway to reconcile economic pursuits with environmental stewardship (Marcon et al., 2022). This research embarks on a comprehensive exploration of GPD, with a particular focus on leveraging recycled and green materials and understanding the intricate dynamics of flexibility, control, and sensitivity during the initial stages of product lifecycle design. The ultimate aim is not only to bridge the existing gaps in the field but also to contribute practical frameworks and methodologies that empower designers and organizations to infuse sustainability seamlessly into the core of their product development processes.

1.1 BACKGROUND:

The concept of "Green Product Design (GPD)" emerged as a response to the escalating environmental concerns that gained prominence in the late 1980s and early 1990s. During this period, the world witnessed a growing awareness of the adverse impacts of industrial growth on the environment (Marcon et al., 2022). Issues such as material scarcity, high energy consumption, rising atmospheric CO_2 levels, global temperature increases leading to ozone depletion, population explosion, and the depletion of natural resources captured the attention of both the public and policymakers. This era marked a critical turning point when environmental considerations began to permeate various aspects of human activities, including industrial processes and product design.

In 1994, the Oslo Roundtable played a pivotal role by providing extensive and early definitions of the term "sustainable," laying the groundwork for discussions on how industries could align their practices with environmental goals. These early definitions set the stage for the evolution of green product design and its applications across diverse industries. According to Aerais (2010), sustainable design aims to integrate product and process design effects with process planning and control. This integration allows for the identification, measurement, evaluation, and management of the flow of environmental waste, with the primary objective of reducing environmental impact.

Vinodh and Rajanayagam (2010) further emphasized the core objective of green production systems – decreasing environmental impact. This is achieved by merging product and process design effects with process planning and control. Green product design, as outlined by Fuller and Ottman (2004), is portrayed as a pragmatic and coherent approach to counteract environmental degradation. Simultaneously, it promises economic and social benefits for customers, stakeholders, and companies. The eco-design practice, as highlighted by Karlsson and Luttropp (2006), aims to combine environmental considerations with business-oriented design goals, reinforcing the idea that sustainable design is not only environmentally conscious but also economically viable.

Despite the growing recognition of the importance of GPD, Howarth and Hadfield (2006) identified a critical gap in the implementation of green principles. Organizations and designers

4

faced challenges in selecting environmentally friendly raw materials, establishing appropriate manufacturing and distribution systems, and determining the use and disposal of final products with minimal environmental impact. This realization underscored the need for a more systematic and comprehensive approach to integrating GPD into industrial practices.
As the global scenario evolved, GPD emerged as a strategy with the potential to provide substantial benefits. Researchers actively contributed to the field, exploring various dimensions and shedding light on the intricate aspects of GPD. However, the study at hand reveals a crucial observation – there is a lack of a systematic approach available for implementation within the design community. Many designers find themselves unable to implement GPD principles due to a dearth of knowledge, limited research, and a lack of concrete methodologies. Instead, a trial-and-error method has been employed by some, leading to inconsistencies and inefficiencies in the execution of green design within organizations.

This difficulty extends beyond individual designers to impact entire organizations attempting to integrate GPD principles into their operational frameworks. The absence of a detailed manual or pragmatic guide compounds the challenges faced by designers and organizations alike. The existing frameworks proposed by researchers lack coherence, a consistent set of elements, and a comprehensive nature. This void in systematic guidance has become a practical impediment for designers eager to contribute to the broader mission of environmental sustainability through effective implementation of GPD principles.

1.2 MOTIVATION:

The motivation behind delving into the realm of Green Product Design (GPD) is rooted in the imperative need to address the pressing environmental challenges that our planet faces today. As the consequences of industrial growth became increasingly apparent in the late 20th century, with issues such as climate change, resource depletion, and pollution taking center stage, the call for sustainable practices became louder and more urgent (Marcon et al., 2022). GPD emerged as a beacon of hope, a tangible pathway towards mitigating environmental impact, fostering economic prosperity, and promoting social well-being.

The global community's acknowledgment of the intricate interplay between human activities and environmental health prompted the articulation of sustainability goals, with GPD positioned as a critical instrument in achieving these objectives. The foundation for this motivation can be traced back to the Oslo Roundtable in 1994, where sustainability was defined with unprecedented clarity. This definition set the stage for a paradigm shift in how industries approached product design and manufacturing, emphasizing the need to harmonize economic pursuits with environmental stewardship.

In the present context, GPD is not just a theoretical concept, but a strategic approach hailed for its potential to provide substantial benefits. Researchers and environmental advocates alike recognize the crucial role GPD plays in steering industries towards a sustainable future. However, this recognition is not without its challenges, and herein lies the core motivation for our exploration.

The current study identifies a critical gap in the application of GPD principles, particularly within the design community. Despite the growing awareness of the need for sustainable practices, a systematic approach for designers to implement GPD effectively appears to be lacking. This observation is the catalyst for our inquiry, driven by the desire to bridge the divide between theoretical knowledge and practical implementation in the field of green design.

One of the primary motivational factors stems from the realization that many designers, armed with the intention to contribute to environmental sustainability, find themselves thwarted by a lack of knowledge, inadequate research, and a dearth of concrete methodologies. The consequence is a reliance on trial-and-error methods, resulting in suboptimal outcomes and an inefficient execution of green design principles. The frustration and challenges faced by designers eager to align their work with environmentally conscious practices highlight the need for a more systematic and accessible approach.

The motivation to delve into the intricacies of GPD is further fueled by the recognition that the implementation of green principles extends beyond individual designers to impact entire organizations. Companies, despite their commitment to sustainable practices, encounter difficulties in integrating GPD into their operational frameworks. This challenge is multifaceted, ranging from selecting environmentally friendly raw materials to establishing sustainable manufacturing and distribution systems and ensuring the responsible use and disposal of final products. The absence of a detailed manual or pragmatic guide compounds the challenges faced by organizations striving to incorporate GPD principles into their day-to-day operations.

Furthermore, the motivation to undertake this study is rooted in the acknowledgment that existing frameworks proposed by researchers lack coherence, a consistent set of elements, and a comprehensive nature. The absence of a standardized and practical guide is not just a theoretical concern; it poses a tangible obstacle for designers and organizations alike, hindering their ability to contribute effectively to the broader mission of environmental sustainability.

As we embark on this exploration, our motivation is not solely to identify gaps and challenges but to contribute meaningfully to the evolution of GPD practices. By dissecting the existing barriers, proposing practical methodologies, and offering insights into the complexities of implementation, we aim to empower designers and organizations to embrace and effectively apply GPD principles. In doing so, we hope to catalyze a positive ripple effect, where green design becomes not just a theoretical ideal but a seamlessly integrated and pragmatic reality, steering industries towards a more sustainable and harmonious future.

1.3 PROBLEM STATEMENT AND RESEARCH GAPS:

The field of Green Product Design (GPD) holds immense promise as a catalyst for addressing environmental challenges, yet a critical examination reveals a substantial gap in its effective implementation. The overarching problem lies in the absence of a systematic and comprehensive approach within the design community, hindering the successful integration of GPD principles into both individual practices and organizational frameworks.

One primary facet of the problem revolves around the limitations faced by designers seeking to implement GPD. Despite an earnest intention to contribute to environmental sustainability, a lack of foundational knowledge and concrete methodologies impedes their progress. The prevailing scenario often sees designers resorting to trial-and-error methods, resulting in suboptimal outcomes and an inefficient execution of green design principles. This not only hampers the efficacy of their efforts but also leads to a potential disheartenment among designers, thwarting the realization of the full potential of GPD.

Moreover, the problem extends beyond individual designers to impact entire organizations attempting to incorporate GPD principles into their operational workflows. Companies, driven by a commitment to sustainability, encounter difficulties in navigating the complexities of green design. From the selection of environmentally friendly raw materials to the establishment of sustainable manufacturing and distribution systems, and ensuring responsible use and disposal of final products, organizations face multifaceted challenges in aligning their operations with GPD principles.

The lack of a detailed manual or pragmatic guide compounds the challenges faced by both designers and organizations. While researchers have proposed various frameworks, these often lack coherence, a consistent set of elements, and a comprehensive nature. This absence of a standardized and practical guide becomes a practical impediment for designers and organizations eager to contribute meaningfully to environmental sustainability through the effective application of GPD principles.

One crucial aspect contributing to the problem is the dearth of a detailed manual or pragmatic guide that designers can refer to during the GPD implementation process. The absence of such a guide creates a significant hurdle, leaving designers in a state of uncertainty about the most effective and efficient strategies to adopt. This lack of a structured roadmap not only slows down the implementation process but also leaves room for inconsistencies and inadequacies in the application of GPD principles.

Furthermore, existing frameworks proposed by researchers lack the coherence needed for seamless adoption by designers and organizations. These frameworks often present a scattered array of elements without a unified and consistent structure. As a result, designers and organizations face difficulties in navigating the complexities of GPD, leading to a lack of confidence in the effectiveness of these frameworks. The absence of a standardized, comprehensive, and coherent guide becomes a critical stumbling block in the path towards widespread and successful implementation of GPD principles.

Additionally, the study identifies a significant gap in the understanding and application of environmental impact assessment techniques. While different techniques have been employed in sustainable materials selection, such as energy content material charts and overall indices for various emissions, the life cycle assessment (LCA) methodology emerges as the most recognized and accepted at the international level. However, even this recognized methodology lacks a designer-friendly format, making it challenging for designers to integrate environmental considerations into their decision-making processes during the early stages of design, such as the concept phase.

10

1.4 RESEARCH AIM AND OBJECTIVES:

1.4.1 Research Aim:

The overarching aim of this research is to advance the field of Green Product Design (GPD) by conducting a comprehensive study of the use of recycled and green materials, examining the role of flexibility, control, and sensitivity in the context of green constraints during the initial stages of the product lifecycle design. Furthermore, the research aims to contribute to the development of a robust and practical framework for GPD, along with the creation of an efficient method to guide designers in developing green product designs. To design the framework for quick and easy "back of an envelope" decision-making, so that an understanding of environmental impacts can be factored into design decisions as early as the concept phase.

Figure 1 highlights key questions that designers face when considering environmental, social, and material impacts during the development of a product.

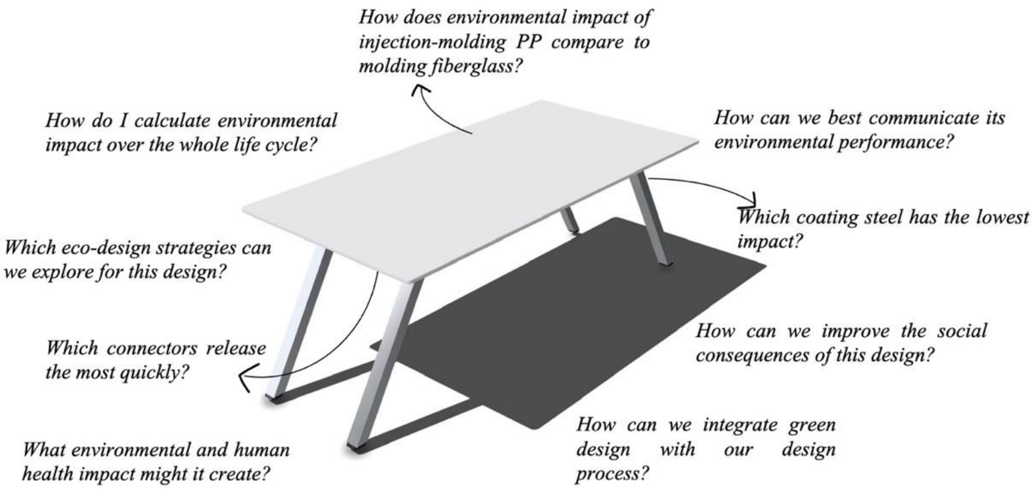

Figure 1: Key Sustainability Questions in Product Design

1.4.2 Research Objectives:

The objectives of the research:

1. To study the green product design using recycled and green materials
2. To study the flexibility, control and sensitivity focusing green constraints in the initial stage of product lifecycle design.
3. To develop the framework for green product design.
4. To develop the method for the practical and efficient approach for developing green product designs.

To Study the Green Product Design Using Recycled and Green Materials:
The first objective of this research is to conduct an in-depth examination of green product design, with a specific focus on the utilization of recycled and green materials. This involves a comprehensive analysis of existing practices, challenges, and opportunities in incorporating recycled and green materials into product design. The research will explore the environmental impact, feasibility, and innovation potential associated with the use of such materials. By achieving this objective, the research aims to provide valuable insights into enhancing sustainable practices in material selection for green product design.

To Study the Flexibility, Control, and Sensitivity Focusing on Green Constraints in the Initial Stage of Product Lifecycle Design:
The second objective is to investigate the role of flexibility, control, and sensitivity in the early stages of product lifecycle design, specifically emphasizing green constraints. This involves an exploration of how design flexibility can accommodate environmental considerations, how control mechanisms can be implemented to ensure adherence to green principles, and how sensitivity to environmental impacts can be integrated into the decision-making process. By studying these aspects, the research aims to uncover strategies and approaches that empower designers to proactively address environmental concerns in the initial stages of product development.

To Develop the Framework for Green Product Design:
The third objective is the formulation of a comprehensive framework for Green Product Design. This involves synthesizing the findings from the study of materials and early-stage

design considerations into a structured and cohesive model. The framework aims to provide a practical guide for designers, incorporating principles of sustainability, recyclability, and environmental impact mitigation. It will consider the entire lifecycle of a product, from material selection to end-of-life considerations, fostering a holistic and integrated approach to green design. The development of this framework serves as a vital contribution to the field, providing a structured methodology for practitioners seeking to embed green principles in their design processes.

To Develop the Method for the Practical and Efficient Approach for Developing Green Product Designs:

The fourth and final objective is the creation of a method that offers a practical and efficient approach for developing green product designs. This method will distill the insights gained from the study of materials, design flexibility, control mechanisms, and environmental sensitivity into a step-by-step guide. The aim is to bridge the gap identified in the problem definition, where designers lacked a systematic approach for implementing GPD principles. This method aims to empower designers with a clear and efficient pathway, ensuring that the incorporation of green elements into product design becomes a streamlined and impactful process.

By achieving these research objectives, the study aspires to contribute significantly to the advancement of Green Product Design practices. The outcomes will not only enhance the understanding of green design principles but will also provide practical tools and frameworks that designers and organizations can readily adopt. Ultimately, the research aims to facilitate a shift towards more sustainable and environmentally conscious product design practices, aligning with the broader goals of mitigating environmental impact and promoting a harmonious coexistence with our planet.

1.5 Scope of the work

This research endeavors to cast a wide net over the intricate landscape of Green Product Design (GPD), encompassing a diverse array of dimensions to offer a holistic and nuanced understanding. The scope includes an extensive exploration of the use of recycled and green materials in product design, delving into their environmental impact, feasibility, and innovation potential. This facet aims to provide a comprehensive overview of current practices and challenges associated with material selection, laying the foundation for sustainable and environmentally conscious choices in the design process.

Furthermore, the research extends its purview to the early stages of the product lifecycle, scrutinizing the role of flexibility, control, and sensitivity within the context of green constraints. By focusing on these crucial aspects, the study aims to uncover strategies that empower designers to make informed decisions aligned with environmental sustainability from the inception of the product design process. The scope also encompasses the development of a robust framework and an efficient method, addressing the identified gaps in the field. The framework will guide designers in adopting green principles seamlessly, ensuring a comprehensive approach to GPD that spans the entire lifecycle of the product. The method, designed for practicality and efficiency, aims to provide a structured pathway for designers and organizations to implement green design principles with clarity and impact. The inclusive scope of this research seeks not only to expand academic knowledge but also to offer practical tools and insights that can be readily applied by professionals in the field, contributing to a paradigm shift towards more sustainable and environmentally responsible product design practices.

CHAPTER 2:

LITERATURE REVIEW

2.1. INTRODUCTION:

In recent decades, the global community has witnessed a significant shift towards sustainable practices across various industries. This transformation is particularly evident in the realm of product design, where the concept of environmental stewardship has become increasingly prominent (Marcon et al., 2022). As businesses strive to mitigate their ecological footprint and meet the growing demand for environmentally responsible products, the field of Green Product Design (GPD) has emerged as a crucial area of focus (Ma et al. 2012).

This chapter presents a comprehensive literature review aimed at elucidating key concepts, frameworks, and challenges pertinent to green product design. Through an exploration of scholarly works, industry publications, and theoretical frameworks, this review aims to provide readers with a thorough understanding of the evolution, significance, and theoretical underpinnings of GPD.

The chapter begins by tracing the evolution and definition of green product design, contextualizing its development within the broader landscape of environmental awareness and sustainability. It then delves into the importance of green materials and processes, highlighting the critical role they play in minimizing environmental impact throughout the product lifecycle. Subsequently, the chapter examines previous frameworks and models in GPD, offering insights into established methodologies and best practices for integrating sustainability principles into product design processes. Moreover, it elucidates the various challenges inherent in implementing GPD, ranging from economic constraints to technological limitations, and explores strategies for overcoming these obstacles.

Finally, the chapter explores theoretical frameworks that underpin green product design principles, drawing upon interdisciplinary perspectives from fields such as ecological economics, industrial ecology, and sustainable design. By synthesizing these theoretical insights with practical considerations, this review aims to equip readers with a comprehensive foundation for understanding and engaging with the complexities of green product design.

2.2. SUSTAINABLE PRODUCT DESIGN VS GREEN PRODUCT DESIGN:

Sustainable Product Design (SPD) and **Green Product Design (GPD)** are both approaches aimed at reducing environmental impacts, but they differ in scope and emphasis.

2.2.1 Definitions

1. **Sustainable Product Design**: This approach encompasses the broader principles of sustainability, focusing on creating products that consider environmental, social, and economic impacts across the entire product lifecycle. Sustainable design aims to minimize resource consumption, reduce pollution, ensure fair labor practices, and promote economic viability.
2. **Green Product Design**: This is a subset of sustainable design that specifically focuses on environmental considerations, aiming to reduce the ecological footprint of a product. Green product design emphasizes minimizing resource extraction, energy consumption,

and waste, primarily through eco-friendly materials, low-impact manufacturing, and recyclability.

2.2.2 Advantages of GDP over SPD

1. **Narrow Focus on Environmental Impact**

   GPD Advantage: GPD directly targets ecological issues like resource depletion, waste management, and pollution, allowing for quick, measurable progress in reducing environmental harm.

   SPD Scope: SPD balances environmental, social, and economic factors, which may dilute the intensity of environmental focus.

2. **Easier to Implement**

   GPD Advantage: Focusing solely on environmental criteria often simplifies decision-making and implementation. It can be easier to prioritize eco-friendly materials, recycling, and energy efficiency without the complexity of addressing social or economic concerns simultaneously.

   SPD Complexity: SPD requires addressing a wide range of sustainability factors, which can make it more challenging to implement holistically.

3. **Cost-Effectiveness**

   GPD Advantage: By targeting environmental aspects alone, GPD may require fewer resources and lower investments compared to SPD, especially when a company lacks the budget for extensive social responsibility programs.

   SPD Cost: SPD's broader approach may involve higher costs due to additional requirements like fair trade materials, worker welfare programs, and other ethical practices.

4. **Enhanced Market Appeal for Eco-Conscious Consumers**

   GPD Advantage: Consumers increasingly prioritize environmental impact, and GPD's focus on "green" elements aligns with this demand. By marketing products as eco-friendly, companies can attract a specific consumer base more effectively.

   SPD Differentiation: SPD appeals to a broader audience but may dilute its message if consumers are primarily interested in environmental benefits.

5. **Faster Product Development Cycles**

   GPD Advantage: Since GPD is focused only on environmental factors, it allows for faster development cycles, as designers focus primarily on material selection, energy efficiency, and end-of-life management.

   SPD Deliberation: SPD requires careful consideration of all three pillars (environmental, social, economic), potentially slowing down the process due to additional complexities.

6. **Easier to Measure and Quantify**

   GPD Advantage: Environmental impacts (like carbon footprint, resource use, waste reduction) are often more quantifiable than social or economic impacts, allowing companies to demonstrate progress more transparently and set clear, achievable goals.

   SPD Metrics: SPD involves complex metrics, including socio-economic indicators, which can be harder to quantify and measure, making progress tracking more difficult.

7. **Regulatory Compliance and Eco-Certifications**
   GPD Advantage: Many regions are implementing environmental regulations and incentives, which GPD can fulfill more directly. GPD's focus on environmental standards aligns well with eco-certification requirements, often easing compliance.
   SPD Certification: SPD may require adherence to additional social and economic standards, making compliance with certification programs more comprehensive and complex.

Summary
While Sustainable Product Design takes a balanced, long-term view across environmental, social, and economic dimensions, Green Product Design's focused approach allows for faster implementation, cost-effectiveness, and a direct appeal to eco-conscious consumers. For companies or projects primarily driven by environmental goals, GPD can offer a more efficient path to meeting their objectives.

2.3. EVOLUTION AND DEFINITION OF GREEN PRODUCT DESIGN:

Green product design, also known as sustainable product design, is a crucial approach aimed at creating products that minimize environmental impact throughout their lifecycle (Vignali 2017). This concept considers various aspects, including raw material sourcing, manufacturing processes, product use, and end-of-life disposal or recycling. Evaluating and defining green product design involves understanding its principles, objectives, and methodologies while reviewing existing definitions from research articles provides insights into its evolving conceptualization within academia and industry (Uctug and Azapagic 2018).

The evaluation of green product design typically involves assessing its adherence to sustainability principles, such as reducing resource consumption, minimizing pollution and waste generation, and promoting social responsibility. Key aspects of evaluation include:

1. ***Life Cycle Assessment (LCA)***: This method assesses the environmental impacts of a product throughout its entire life cycle, from raw material extraction to disposal (Favi et al. 2018). It helps identify areas for improvement and informs decision-making in design and production.
2. ***Material Selection***: Green product design emphasizes the use of eco-friendly and renewable materials, as well as those with lower environmental footprints. Evaluating material choices involves considering factors like resource availability, toxicity, recyclability, and biodegradability (Elduque et al. 2014).
3. ***Energy Efficiency***: Products should be designed to minimize energy consumption during production, use, and disposal stages. Evaluating energy efficiency involves analysing processes, components, and technologies to identify opportunities for optimization (Pina et al., 2015).
4. ***Waste Reduction***: Green product design aims to minimize waste generation by adopting strategies like modular design, efficient manufacturing processes, and product reuse or recycling options (Hischier 2015). Evaluation includes quantifying waste generation and identifying ways to reduce or eliminate it.
5. ***Functionality and User Experience***: Sustainable products must meet consumers' needs and expectations while providing environmental benefits. Evaluation involves assessing product performance, usability, and overall satisfaction to ensure a positive user experience (Hernández-de-Anda et al., 2023).

Defining green product design requires clarity on its scope, objectives, and guiding principles. Various definitions have emerged in research articles, reflecting different perspectives and priorities. Reviewing these definitions can help identify common themes and areas of divergence, contributing to a comprehensive understanding of the concept as shown below in Table 1.

Table 1: Some key definitions of green product design from research literature include:

S. No.	Authors	Used definition
1.	de Medeiros and Ribeiro	"**Green products**, also named **environmentally correct** or **environmentally-sustainable products**, are those capable of adding long-term benefits, reduce client stress and relieve them from their environmental responsibility, without, however, diminishing products' satisfying qualities."
2.	Biswas and Roy	"The **environmentally sustainable** or **environmental compatible** or **green products** entails a list of potential benefits to the environment as they are made of environmental-friendly resources, have resource-conservation potential, can be recycled and have least environmental impact at all stages of its lifecycle."
3.	Kang and Choi	"**Sustainable products**, in this study, are broadly defined as those that embrace positive social, environmental, and ethical attributes (Luchs *et al.*, 2010)."
4.	Maniatis	"The concept of **green products** is related to sustainable manufacturing and supply chain management, which involves environment friendly, planet friendly, and people friendly standards, technologies and practices (Palevich, 2012). The concept of green is extended to almost every process step of procuring raw materials, producing, storing, packaging, shipping, and distribution of products (Palevich, 2012)."
5.	Moser	"Generally, **green products** are defined as products that are less or not at all harmful for the environment in comparison to a substitute of the same product category."
6.	Saluja	"In general, **green products** also known as **environmentally friendly products** or **ecological products**. Pavan (2010) stated, green products are the products which protect or enhance the natural environment by conserving energy or resources, recyclable and reusable, original grown, reducing or eliminating use of toxic agents, pollution and waste, contain natural ingredients or recycled content, do not pollute the environment, contain approved chemicals and have not been tested on animals."
7.	Borella and Barcellos	"**Green product** is the product designed to contemplate its relationship with the environment, causing no harm to nature. Sustainable products are conceived since the choice of raw materials until its use and discard, through a renewing cycle that will not bring any damage to future generations. Just as nature has a life cycle, the products must also have."
8.	Esmaili and Fazeli	"**Green products** contain elements that are not harmful to the environment (Mahenc, 2008) and (Polonsky and Rosenberger, 2001) made of materials that can be recycled to provide product (Dangelico and Pontrandolfo, 2010), (Chen and Chai, 2010). Its production process is environmentally friendly (Gura ̆u and Ranchhod, 2005)."
9.	Esp ́ınola-Arredondo and Mun ̃oz-Garc ́ıa	"**The brown and green goods** differ both in their attributes and in their environmental features. **A green good** generates less pollution than a brown product, which can become zero when the good is sufficiently clean (low pollution intensity)."

10.	Ec.europa.eu	"**Environmental products** are goods and services that are produced for the purpose of preventing, reducing and eliminating pollution and any other degradation of the environment (environmental protection - EP) and preserving and maintaining the stock of natural resources and hence safeguarding against depletion."
11.	Jasti *et al.*	"It is defined that development of product that meets the requirement of the present without sacrificing the ability of the future generation to achieve their own requirements."
12.	Johnstone and Tan	"**Environmentally friendly (EF) products** have been defined as products that consumers perceive to be environmentally friendly, whether it is due to the types of materials used, the production process, packaging, promotion, and so on."
13.	Mohd-Suki	"**Green products**, also known as **ecologically** and **environmentally friendly products**, include products that incorporate recyclable and recycled content, and contain less toxic chemical substances which minimize the impact on the environment."
14.	Ritter *et al.*	"The definition of **green products** can highlight different aspects of these products: the life cycle phases during which a product can show its environmentally friendly features, the higher environmental benefits compared to conventional products, or the minimization of the natural resources used."
15.	de Medeiros *et al.*	"**Green products** are those that hold the potential to aggregate long-term benefits, reduce consumer stress and ameliorate customer environmental responsibilities while maintaining its positive qualities."
16.	Haws *et al.*	"**Environmentally friendly product**: one with at least one positive environmental attribute. An "environmental attribute" is an attribute that reflects the impact of the product on the environment. As such, environmental product attributes can be positive (i.e., the product has little to no negative impact on the environment and is considered environmentally friendly) or negative (i.e., the product harms the environment)."
17.	Driessen *et al.*	"**Green products** are defined as new products whose greenness is significantly better than conventional or competitive products. Greenness is continuous rather than dichotomous. "Green" products represent a significant improvement in greenness, which can be either small or large, whereas "non-green" refers to no or an insignificant improvement in greenness."
18.	Mattioda *et al.*	"**Sustainable products** can be defined as those that offer environmental, social and economic benefits while protecting public health, welfare and the environment (Lu *et al.*, 2011)."
19.	Tomasin *et al.*	"**Green products** are designed to prevent, limit, reduce, and/or correct harmful environmental impacts on water, air, and soil. Accordingly, these products constitute at least one means of resolving problems related to waste, noise, and general detriments to ecology while serving as an avenue for generating beneficial products and services (OECD, 2009)."
20.	Tseng and Hung	"**Green products**, namely, environmentally friendly products or environmentally conscious products, are referred to as products designed to lessen the consumption of natural resources required and minimize the adversely environmental impacts during the whole life-cycles of these products."
21.	Chen and Chang	"**Green products** are those that have less of an impact on the environment, are less detrimental to human health, are formed or part-

		formed from recycled components, are manufactured in a more energy conservative way, or are supplied to the market with less packaging."
22.	Kam-Sing Wong	"**A green and innovative** product is a product characterized by its taking into account of the recyclability and disposal issues throughout its life cycle; usage of materials which are recycled and recyclable and which are less polluting, non-polluting or non-toxic; due consideration to energy use, human toxicity, ecological impact and sustainability issues at every stage of its life cycle; and incorporation of a continual impact assessment and improvement mechanism in the product development cycle."
23.	Blengini *et al.*	"A **sustainable product** could be: a product designed, manufactured, used and disposed of according to criteria of economic, environmental and social efficiency, which maximize net benefits across generations. However, it should be mentioned that there is still much confusion about what can be considered a sustainable product and what should not."
24.	Wee *et al.*	"**Green products** are designed to reduce energy consumption, use less natural resources, raise the recycled materials, and reduce or eliminate toxic substances, which are harmful to both the environment and human health. The development of a green product is a process within the internal processes of a company."
25.	Air Quality Sciences, Inc.	"**Environmentally friendly** refers to products or services that are not harmful to the outdoor environment or its inhabitants, the term is quite vague and subject to multiple interpretations, "green" is "a difficult word."
26.	Chen and Chai	"In general, **green product** is known as an **ecological product** or **environmental friendly product**."
27.	Dangelico and Pontrandolfo	"**Green products** are characterized according to their environmental impact (less negative, null, and positive) whose meaning is slightly different according to each of the three environmental focus (materials, energy, and pollution)."
28.	Durif *et al.*	"A **green product** is a product whose design and/or attributes (and/or production and/or strategy) use recycling (renewable/toxic-free/biodegradables) resources and which improves environmental impact or reduces environmental toxic damage throughout its entire life cycle". Note that each code contains several synonymic terminologies. Green: "environmental" or "ecological"; Attributes: "functions", "ideas", "practices", or "qualities"; Uses: "incorporates"; Recycling: "renewable", "toxic-free", or "biodegradable"; Resources: "energy", "materials", or "ingredients"; Benefits: "maximizes", "encourages", or "contributes"; Reduces: "minimizes", "saves", or "eliminates", and Toxic damage: "pollution"."
29.	Gao *et al.*	"**Green product** is a kind of product that has no or little harmful performance on ecological environment and has a higher rate of resource and energy utilization. The concept of green product is a whole product's life cycle rather than a certain process or stage, so the information model of green product should meet the following requirements: (1) include the information of fundamental function and structure; (2) include the fundamental information of the product's life cycle; and (3) provide data for environmental performance assessment."
30.	Panjaitan and Sutapa	"**Green Product** is eco-friendly products or products that in their planning and process with technique have less impact to environment, even in production process, distribution, and consumption."

31.	U.S. Department of Commerce, Economics and Statistics Administration	"We defined **green products or services** as those whose predominant function serves one or both of the following goals: conserve energy and other natural resources or reduce pollution."
32.	Albino *et al.*	"**Green product**: goods or services designed to minimize their impact on the environment at each phase of their life cycle. In particular, non-renewable resource use is minimized, toxic materials are avoided, and renewable resource use takes place in accordance with their rate of replenishment."
33.	Yanarella *et al.*	"**Green** is typically associated with individual products and processes. Green practices are ideologically safe practices that do not fundamentally disturb the driving forces of economic growth and corporate profit-making."
34.	Pickett-Baker and Ozaki 2008 Seuring and Mu¨ ller	"If a product has a low environmental impact, it is regarded as an **environmentally sustainable product.**"
35.	Seuring and Mu¨ ller	"**Sustainable product** is the term used to comprehend all kinds of products that have or aim at an improved environmental and social quality, which can be related back to the already mentioned implementation of environmental and social standards."
36.	D' Souza *et al.*	"**Green products** have to represent a significant achievement in reducing environmental impact; they may also have to incorporate strategies of recycling, recycled content, reduced packaging or using less toxic materials."
37.	Nimse *et al.*	"**Green products** may be defined as products that contain recycled materials, reduce waste, conserve energy or water, use less packaging, and reduce the amount of toxics disposed or consumed. These products are less harmful on humans and their environment compared with the traditional products in use, and are more socially, economically, and environmentally viable in the long run."
38.	Hartmann and Apaolaza-Iba´n˜ez	"**Green product attributes** may be environmentally sound production processes, responsible product uses, or product elimination, which consumers compare with those possessed by competing conventional products."
39.	Ottman *et al.*	"Although no consumer product has a zero impact on the environment, in business the terms '**green**' or '**environmental product**' are used commonly to describe those that strive to protect or enhance the natural environment by conserving energy and/or resources and reducing or eliminating use of toxic agents, pollution, and waste."
40.	Gura˘u and Ranchhod	"**Ecological product** is defined as a product that was manufactured using toxic-free ingredients and environmentally-friendly procedures, and who is certified as such by a recognized organization."
41.	Soo-Wee and Quazi	"**Green product/ process design**: Design production processes and products in such a way that it minimizes adverse impact on the environment. Life cycle analysis used to assess the environmental impact of products throughout the entire life span of the products. Products are redesigned to reduce the negative environmental impact. Production processes are examined to reduce the amount of waste, energy consumption and emissions. Adopt a preventive approach and integrate environmental concerns into the product during its design

		phase. Recycling activities carried out to ensure full usage of resources.”
42.	2003 Osada	“**Eco-product, ecological product, green product** is one that contributes to environmental protection or preservation.”
43.	2002 Janssen and Jager	“**Green products** are products with low environmental impacts. They are defined as products with an alternative design such that less physical resources are required during its life cycle.”
44.	Commission of the European Communities	“**Green products**, defined as products that ’use less resources, have lower impacts and risks to the environment and prevent waste generation already at the conception stage have been recognized as the engine of a ’ new growth paradigm and a higher quality of life through wealth creation and competitiveness’.”
45.	Organization for Economic Cooperation and Development.	“**Environmental goods and services** include all activities that measure, prevent, limit, minimize or correct environmental damage.”
46.	Ottman	“**Green products** are typically durable, non-toxic, made of recycled materials, or minimally packaged. Of course, there are no completely green products, for they all use up energy and resources and create by-products and emissions during their manufacture, transport to warehouses and stores, usage, and eventual disposal. So green is relative, describing products with less impact on the environment than their alternatives.”
47.	Reinhardt	“**Environmental product differentiation** takes place when: “a business creates products that provide greater environmental benefits, or that impose smaller environmental costs, than similar products.”
48.	Nissen	“An **eco-product** should be designed in such a way that: the chosen material is a plentiful natural resource; the manufacturing process requires only a low consumption of natural resources; the emission of hazardous waste in the production process is minimal; when in use is relatively environmentally sound; environmentally sound remanufacturing or recycling processes can be easily applied after use; when finally discarded, the environmental impact of the disposal/incineration is minimal.”
49.	Peattie	“**Green product**: when its environmental and societal performance, in production, use and disposal, is significantly improved and improving in comparison to conventional or competitive products offerings.”
50.	Chen	“**Green product development** should focus on the entire production process (from manufacturing to disposal) and not just on the product itself. Businesses and environmentalists often have different opinions on "greenness". Most companies think "greenness" as minimizing waste, while for environmentalists is sustainability.”
51.	Herberger	“**Ecological Product**s are products that have been identified as having an ecological orientation. Ecology appeal, from a consumers’ perception, means that among the product’s characteristics its viability with the environment is recognizable, understandable and marketable.”

By evaluating and synthesizing these definitions, green product design may be defined as ***“Green Product are those which should have least impact on environment during and after it’s whole life cycle.”***

By using this definition researchers and practitioners can develop a comprehensive understanding of green product design, guiding its implementation and advancement towards a more sustainable future.

2.4. STUDY OF GREEN PRODUCT DESIGN USING RECYCLED AND GREEN MATERIALS:

The pursuit of sustainable development has prompted a significant shift in various sectors towards environmentally friendly practices, including product design. Within this paradigm, the concept of green product design, particularly employing recycled and green materials, has emerged as a pivotal strategy for reducing environmental impact and promoting circularity in resource usage.

Recycled Materials in Product Design**:** The utilization of recycled materials offers a compelling solution to mitigate the environmental burden associated with conventional manufacturing processes. By repurposing post-consumer or post-industrial waste streams, designers can divert materials from landfills and reduce the demand for virgin resources (Tannous et al. 2018). Moreover, incorporating recycled materials into product design fosters closed-loop systems, where products are continually recycled and reintegrated into the production cycle, thus reducing the overall ecological impact (Rubin et al. 2014).

Numerous studies have explored the feasibility and efficacy of incorporating recycled materials into various product categories, ranging from packaging and textiles to electronics and construction materials (Vezzoli & Manzini, 2008). These investigations have highlighted the technical, economic, and environmental challenges associated with integrating recycled content, such as material quality, supply chain constraints, and market demand. However, they also underscore the potential benefits in terms of reduced environmental footprint, enhanced brand reputation, and regulatory compliance (Toketemu, 2018).

Green Materials and Biodegradability**:** In addition to recycled materials, the adoption of green materials, characterized by renewable sourcing and biodegradability, has gained traction in sustainable product design. Green materials, such as bio-based polymers, natural fibers, and bio composites, offer alternatives to traditional petroleum-derived plastics and synthetic materials, which are often non-renewable and non-biodegradable (Felton & Bird, 2007).

Research in this domain has explored the properties, performance, and environmental impact of green materials across diverse applications. Studies have investigated the mechanical properties, degradation kinetics, and end-of-life scenarios of biodegradable polymers, assessing their suitability for various product contexts. Furthermore, advances in bio-based materials derived from agricultural residues, algae, and other renewable sources hold promise for reducing reliance on fossil fuels and minimizing ecological harm (Maccioni et al., 2019).

Green Processes in Product Manufacturing**:** Beyond material selection, the adoption of green processes in product manufacturing plays a crucial role in enhancing sustainability (Rehman et al., 2017). Green processes encompass a range of practices aimed at minimizing energy consumption, emissions, and waste generation during manufacturing operations. These include energy-efficient production techniques, such as lean manufacturing, renewable energy utilization, and process optimization through lifecycle assessment (LCA) methodologies (Bloch, 1995).

Studies have demonstrated the efficacy of green processes in reducing environmental impact and improving resource efficiency across various industries. For instance, initiatives such as eco-design, design for disassembly, and remanufacturing emphasize the importance of incorporating environmental considerations into manufacturing processes to prolong product lifespan and facilitate end-of-life recovery (Zhang et al., 2016).

***Challenges and Opportunities*:** Despite the growing interest in green product design using recycled materials and green processes, several challenges persist in realizing its full potential. Technical limitations, such as material compatibility, durability, and performance standards, pose obstacles to widespread adoption (Mazzi, 2020). Moreover, economic factors, including production costs, market demand, and regulatory frameworks, influence the feasibility of sustainable design practices.

However, amidst these challenges lie opportunities for innovation, collaboration, and systemic change. Interdisciplinary research efforts, involving designers, engineers, scientists, policymakers, and stakeholders, can foster synergies and address multifaceted sustainability challenges. Furthermore, advancements in material science, recycling technologies, green processes, and circular business models offer pathways for overcoming barriers and accelerating the transition towards a more sustainable future.

2.5. FLEXIBILITY, CONTROL, AND SENSITIVITY IN GREEN PRODUCT DESIGN

The incorporation of adaptability, regulation, and examination of potential outcomes has become a crucial framework in the field of environmentally friendly product design, making a substantial contribution to the progress of sustainable practices. This section explores the literature related to these topics, emphasizing their significance and practical use in the context of designing environmentally friendly products.

Adaptability in the Design of Environmentally Friendly Products: Product design flexibility refers to a product's ability to adjust and develop in response to changing market demands, technical advancements, and environmental factors. It includes many elements, including modularity, versatility, and adaptability, all focused on improving the durability and sustainability of products (Zhang et al., 2016).

Modular design enables the convenient assembly and disassembly of product components, hence facilitating the processes of repair, maintenance, and upgrades. This not only extends item durability, but also reduces resource utilization and waste production. Furthermore, adaptable manufacturing procedures allow for product customization and personalization, effectively meeting the varied tastes of consumers while reducing the occurrence of overproduction and surplus inventories (Newcomb et al., 1996).

Furthermore, the utilization of adaptable materials and production methods allows for the creation of items that may be reused or recycled once they reach the end of their useful lives, thereby supporting the implementation of a circular economy model (Molloy et al., 2012). Manufacturers can achieve environmental sustainability, economic viability, and social responsibility by adopting a flexible approach to design.

Regulating Mechanisms for Sustainable Practices: Control techniques are essential for ensuring that green product design adheres to sustainability objectives. These mechanisms involve various tactics and instruments that are designed to monitor, evaluate, and manage the environmental performance of products from start to finish (Tran & Adomako, 2022).

Environmental management systems (EMS) offer a systematic framework for incorporating environmental factors into product development processes. EMS, or Environmental Management Systems, allow firms to conduct thorough assessments and audits to identify areas that need improvement and take action to reduce environmental consequences (Klöpffer & Grahl, 2014). Life cycle assessment (LCA) methodologies improve the assessment of products' environmental impact by examining many elements, such as raw material extraction, manufacture, distribution, usage, and disposal.

Furthermore, the use of supply chain management methods is crucial in fostering sustainability in the context of green product design. Companies may promote ethical procurement of resources, decrease carbon emissions from transportation, and minimize waste generation by supporting openness and accountability across the supply chain (Tran & Adomako, 2022).

Performing sensitivity analysis to evaluate optimized design solutions: Sensitivity analysis is a useful technique for designers who want to optimize green product designs. It helps identify important characteristics and assess their influence on environmental performance. By evaluating the responsiveness of design elements to variations in environmental parameters, designers can make well-informed choices to reduce environmental impacts and enhance sustainability (Maddulapalli et al., 2007).

Sensitivity analysis allows designers to examine multiple scenarios and evaluate the environmental consequences of different design decisions, including potential trade-offs (Sage, 1981). This iterative method enables the creation of optimal solutions that strike a compromise between competing objectives, such as performance, cost, and environmental effect.

In addition, sensitivity analysis can provide valuable insights for decision-making at several stages of the product development process, ranging from the choice of materials and production methods to the enhancement of packaging and distribution tactics (Henriksen et al., 2021). By incorporating sensitivity analysis into the design workflow, designers can actively tackle environmental limitations and promote ongoing enhancement in green product design.

To summarize, the integration of adaptability, management, and examination of potential outcomes in the development of environmentally friendly products provides a holistic structure for achieving sustainability goals. By embracing these principles, designers can create adaptive, environmentally friendly goods that align with the ideals of a circular economy.

2.6. SINGLE-FIGURED LIFE CYCLE ASSESSMENT (LCA) METHOD

The single-figured Life Cycle Assessment (LCA) method is an innovative approach that simplifies the complex and multifaceted process of traditional LCA by focusing on a single environmental impact category, typically carbon emissions (Favi et al. 2018). This method has gained attention in the field of sustainable product design due to its practicality and ease of use, making it a valuable tool for designers, manufacturers, and stakeholders who need to make informed decisions with limited time or expertise in environmental science.

2.6.1 Overview of the LCA Methodology

Traditional Life Cycle Assessment (LCA) is a comprehensive process used to evaluate the environmental impacts associated with all stages of a product's life—from raw material extraction (cradle) through manufacturing, use, and disposal (grave) (Grignon-Massé, Rivière, and Adnot 2011). LCA examines multiple impact categories, such as global warming potential, ozone depletion, water use, resource depletion, and toxicity, among others. While thorough, this approach can be data-intensive and complex, often requiring expert interpretation and significant resources to conduct and analyze (Ma et al. 2012).

In contrast, the single-figured LCA method narrows the focus to one key metric, most commonly carbon emissions measured as CO_2 equivalents (CO_2e). This approach aims to streamline the assessment process, making it more accessible and actionable, especially in contexts where carbon footprint is the primary environmental concern.

2.6.2 Focus on Carbon Emissions

Carbon emissions are a major contributor to global climate change, making them a critical metric in the evaluation of environmental sustainability Hawthorne and (Ameta 2012). The single-figured LCA method leverages this focus to provide a clear, quantifiable measure of a product's impact on climate change, which is directly linked to its carbon footprint. By concentrating on CO_2e, this method allows for a more straightforward comparison between different products, materials, or design choices based on their carbon impact.

The method's reliance on carbon emissions as the sole metric is particularly valuable in industries where reducing greenhouse gas emissions is a priority, such as in manufacturing, transportation, and consumer goods. It provides a tangible target for sustainability efforts, allowing organizations to benchmark their performance against industry standards or regulatory requirements.

2.6.3 Application Across Lifecycle Phases

The single-figured LCA method can be applied across all phases of a product's lifecycle, ensuring a comprehensive assessment of carbon emissions from cradle to grave. The main lifecycle phases include:

1. **Manufacturing Phase:** This phase typically involves significant carbon emissions due to the energy-intensive processes of material extraction, processing, and product assembly. The single-figured LCA method evaluates emissions associated with these activities, offering insights into how material choices and manufacturing processes can be optimized to reduce carbon output.

2. **Use Phase:** During the use phase, carbon emissions are primarily driven by the energy required to operate the product. For energy-intensive products, such as electronics or vehicles, this phase can contribute substantially to the overall carbon footprint. The single-figured LCA method assesses the emissions over the product's operational life, guiding design improvements aimed at energy efficiency and reduced carbon emissions.

3. **End of Life Phase:** The end-of-life phase addresses the disposal, recycling, or treatment of the product. The single-figured LCA method evaluates the carbon emissions

associated with these activities, promoting design strategies that facilitate recycling, reduce waste, and minimize the environmental impact of disposal processes.

2.6.4 Advantages of the Single-Figured LCA Method

1. **Simplicity and Accessibility:** One of the primary advantages of the single-figured LCA method is its simplicity. By focusing on carbon emissions, the method reduces the complexity of traditional LCA, making it more accessible to product designers, engineers, and decision-makers who may not have specialized expertise in environmental assessment.

2. **Actionable Insights:** The method provides clear, actionable insights that can be directly applied to product design and development. By offering a single figure that represents the carbon footprint, the method enables quick comparisons between design alternatives, facilitating more sustainable choices in the early stages of product development.

3. **Enhanced Communication:** The single-figured approach simplifies the communication of environmental impacts to stakeholders, customers, and regulatory bodies. A single carbon emission figure is easier to understand and communicate, supporting transparency and informed decision-making across the supply chain.

2.6.5 Limitations and Considerations

While the single-figured LCA method offers many advantages, it is important to recognize its limitations:

1. **Narrow Focus:** The primary limitation of this method is its narrow focus on carbon emissions. By concentrating solely on this metric, the method may overlook other significant environmental impacts, such as water usage, toxicity, or resource depletion. As a result, there is a risk that important environmental trade-offs could be missed.

2. **Potential for Oversimplification:** The simplification inherent in reducing multiple environmental impacts to a single figure can lead to oversimplification, potentially obscuring the complexities of environmental sustainability. It is crucial for users of the single-figured LCA method to remain aware of these limitations and consider complementary assessments when necessary.

2.6.6 Relevance to Green Product Design

In the context of green product design, the single-figured LCA method is particularly relevant. It aligns with the goals of reducing the carbon footprint of products and processes, which is a key aspect of sustainability. By integrating this method into the design process, companies can ensure that carbon emissions are a central consideration from the outset, leading to more environmentally responsible products.

Moreover, the method's simplicity and focus on a single, quantifiable metric make it an ideal tool for designers who need to make quick, informed decisions without getting bogged down in the complexities of full-scale LCA. This approach facilitates the development of products that are not only sustainable but also competitive in markets where environmental impact is increasingly becoming a key differentiator.

2.6.7 Conclusion

The single-figured LCA method represents a significant step towards making life cycle assessment more practical and accessible, especially for those focused on reducing carbon emissions. Its application in green product design is both relevant and effective, providing a clear pathway for minimizing environmental impact throughout the product lifecycle. While it has limitations, particularly in its narrow focus, its advantages in simplicity, ease of communication, and actionable insights make it a valuable tool in the pursuit of sustainable product development.

2.7. PREVIOUS FRAMEWORKS AND MODELS IN GPD

In the realm of Green Product Design (GPD), numerous frameworks and models have been proposed by researchers and practitioners to guide the integration of sustainability principles into product development processes. These frameworks aim to provide structured methodologies for incorporating environmental considerations into various stages of product design, from conceptualization to end-of-life management.

However, the present study reveals a noteworthy trend in the development of these frameworks. Many researchers have introduced novel models and frameworks based on their conceptual knowledge and experience, rather than conducting extensive literature surveys. These frameworks often lack a solid foundation in existing research and may result in a disjointed set of elements within the field of GPD. Moreover, the study notes a dearth of efforts to critically review and build upon existing frameworks, hindering the progression towards a coherent body of knowledge in GPD.

Despite these challenges, several frameworks have been published in research papers, each offering unique perspectives and methodologies for green product design. Some notable frameworks include:

11

1. ***Life Cycle Assessment (LCA)*****:** This framework evaluates the environmental impacts of a product throughout its entire lifecycle, from raw material extraction to disposal. LCA helps identify areas for improvement and guides decision-making towards more sustainable design choices.

2. ***Design for Environment (DfE)*****:** DfE frameworks focus on designing products that
12 minimize environmental impacts by considering factors such as material selection, energy efficiency, and end-of-life disposal. These frameworks emphasize the importance of proactive environmental considerations during the design phase.

3. ***Cradle-to-Cradle (C2C) Design*****:** Inspired by the concept of the circular economy, C2C frameworks aim to create products that can be continually recycled or repurposed without generating waste. This approach prioritizes the use of renewable materials and encourages innovative design solutions for closed-loop product systems.

4. ***Sustainable Product Development (SPD) Frameworks*****:** These frameworks integrate sustainability principles into traditional product development processes, emphasizing the need for interdisciplinary collaboration, stakeholder engagement, and lifecycle thinking.

While these frameworks offer valuable insights and methodologies for green product design, there is a pressing need for further research to critically evaluate and refine existing approaches. As noted by Soni and Kodali (2013), the development of frameworks based on comprehensive literature reviews can lead to more coherent and implementable models. Additionally, the inclusion of perspectives from academicians, practitioners, and consultants can enrich the development process and enhance the applicability of GPD frameworks in real-world contexts.

Moving forward, it is essential for researchers and practitioners in the field of GPD to collaborate, critically evaluate existing frameworks, and identify opportunities for innovation and improvement. By building upon the foundations laid by previous research and incorporating diverse perspectives, the field can advance towards more sustainable and impactful product design practices.

2.8. CHALLENGES IN IMPLEMENTING GPD

Implementing Green Product Design (GPD) poses various challenges for organizations seeking to integrate sustainability principles into their product development processes. These challenges span economic, technological, regulatory, and cultural dimensions, requiring multifaceted strategies to address effectively. Here's a detailed exploration of the challenges:

1. ***Cost Considerations*:** One of the primary challenges in implementing GPD is the perception that sustainable practices may lead to increased costs. Green materials and processes often come at a premium, making it difficult for organizations to justify investment in sustainability without clear economic incentives (Więckowski et al., 2023). Moreover, the lack of standardized cost-benefit analyses for green initiatives complicates decision-making processes.

2. ***Technological Limitations*:** Adopting green materials and processes may require technological advancements or infrastructure upgrades, which can pose practical challenges for organizations, especially small and medium-sized enterprises (SMEs). Limited access to green technologies and expertise may hinder the adoption of sustainable practices, particularly in industries with complex manufacturing processes (Zhou, 2023).

3. ***Regulatory Compliance*:** Compliance with environmental regulations and standards adds another layer of complexity to GPD implementation. Organizations must navigate a complex landscape of environmental laws, certifications, and reporting requirements, which may vary across regions and industries (Klöpffer & Grahl, 2014). Failure to comply with regulations can result in legal liabilities, fines, and reputational damage.

4. ***Consumer Preferences*:** While there is a growing demand for environmentally friendly products among consumers, preferences can be fickle and influenced by various factors such as price, convenience, and brand reputation. Organizations must carefully balance sustainability goals with consumer expectations to ensure market acceptance of green products (Hopfe, 2009). Moreover, effectively communicating the environmental benefits of products to consumers remains a challenge.

5. ***Supply Chain Complexity*:** GPD implementation often involves collaboration with suppliers to ensure the use of sustainable materials and practices throughout the supply chain (Sage, 1981). However, managing and monitoring supplier compliance can be

challenging, particularly in global supply chains with multiple tiers of suppliers. Limited transparency and traceability pose risks of greenwashing and ethical issues.

6. ***Organizational Culture and Resistance to Change*:** Shifting towards a culture of sustainability requires organizational buy-in and employee engagement at all levels. Resistance to change, entrenched practices, and lack of awareness or training can impede GPD implementation efforts (Hambali et al., 2009). Building internal capacity and fostering a culture that values environmental stewardship are essential for long-term success.

7. ***Measuring and Reporting Impact*:** Assessing the environmental performance and impact of green products requires robust metrics and measurement tools. However, existing frameworks for evaluating sustainability metrics may be inadequate or lack consensus, making it challenging to accurately measure and communicate the benefits of GPD initiatives to stakeholders (Pianosi et al., 2016).

Addressing these challenges requires a holistic approach that integrates environmental considerations into all aspects of product development, from design and procurement to marketing and end-of-life management. Collaboration across disciplines, sectors, and stakeholders is essential for overcoming barriers and driving meaningful progress towards more sustainable and responsible product design practices.

CHAPTER 3:

METHODOLOGY

3.1 RESEARCH APPROACH:

The research approach outlines the systematic methods and processes used to conduct the study. In this thesis, the primary research approach is a systematic literature review, focusing on developing a conceptual framework for green product design based on a single-figured Life Cycle Assessment (LCA) method. This systematic literature review can be classified as one aiming for model/framework development, like Paul and Mas (2019). Systematic literature reviews provide a rigorous and transparent process aimed to exhaustively synthesize research contributions on a given field based on an explicit and replicable algorithm (Tranfield et al., 2003).We used the Preferred Reporting Items for Systematic Literature Reviews and Meta-Analyses (PRISMA) as a guiding protocol to increase robustness of the systematic literature review (Moher et al., 2017). PRISMA provides a set of steps and guidelines for the improvement of the reporting of systematic literature reviews, such as: protocol description, eligibility criteria, search sources, data collection process specification (Moher et al., 2017).

3.2 SYSTEMATIC LITERATURE REVIEW

This Literature Review followed three major phases adapted from the recommendations of Tranfield et al. (2003) and Denyer and Tranfield (2009): (i) Exploration; (ii) Execution and Systematization; and (iii) Synthesisation and Reporting.

3.2.1 The Exploration Phase:

This phase defines important criteria for the protocol. Initially, we searched several databases with terms related to Environmentally Sustainable Product Design, Eco-Friendly Product Design and Green Product Design. The retrieved articles were scanned, and the most relevant studies were examined to search for potential keywords to make sure that our searches encompassed the adequate terms, since green product attributes have several synonyms. Based on the exploratory research, we combined two groups of words. The terms of the first group of synonyms for green product ("Sustainable product" OR "Sustainable products" OR "Green product" OR "Green products" OR Environment* friendly* product) were individually combined with each of the following keywords: green product design, product design attribute, green product feature, and product design framework. After this initial step, we decided to include another batch of possible synonyms for green products based on the insights from the first search. Thus, we combined the second group of synonyms ("eco-friendly" OR "eco product" OR "eco design" OR "green design") with each individual term (green product design, product design attribute, green product feature, and product design framework) in individual searches. It is reasonable to argue that these keywords are the main ones used in the green product literature and articles in this field are expected to use at least one of the variations searched in the title, abstract, or keywords.

Following the recommendations of PRISMA, query string searches. started in October 2019 and were followed by several follow-up searches until Dec 2023 which aimed to capture any possible new publication on the topic. Initial dates for publications were not established, since we aimed to retrieve articles published at any time. We searched two of the most relevant academic databases: ScienceDirect® and Scopus®. Scopus is the largest citation database of peer-reviewed literature (Elsevier, 2020), whereas Science Direct hosts over 3.800 journals

(Elsevier, 2023). These databases are particularly suitable for systematic reviews on sustainability since they comprise the full list of the top publications on sustainable development classified by Google Scholar (Google Scholar, 2023).

3.2.2 Execution and Systematization

We searched both databases using the following eligibility and inclusion criteria: keywords should be in the Title, Keywords, and Abstract; only research papers in Journals were considered, and we filtered for articles published in the English language. The fourth inclusion criteria referred to the selection of articles that addressed green product attributes and it was employed in the next step. Figure 2 presents the combinations used for the searches which resulted in a total of 5271 articles (1738 from ScienceDirect and 3533 from Scopus). After articles were retrieved, we used a systematic literature review aiding software (StArt – State of the Art through Systematic Review tool) to assist in the organization and selection of the articles, which was conducted independently. The full set of 5271 articles was loaded on the software. 1504 duplicates were removed. Then, titles, keywords, and abstracts were screened to check for fit based on the research questions and this paper's topic and on the eligibility criteria previously established (as recommended by PRISMA). As a result, 3685 non-relevant articles were excluded for not addressing the research objective. We excluded documents that did not address green product attributes. Our large exclusion rate can be explained by two reasons: first, the environmental sustainability research field uses several different synonyms, which had to be included in the systematic searches to encompass all relevant contributions, and consequently, exponentially increase the number of articles retrieved. Secondly, several papers from chemical engineering, materials engineering, and similar fields were retrieved since they report findings of green characteristics/features from new materials and products developed. To exclude articles, we read their title, abstract, and keywords to check if they studied green products and had to, separately, analyse the title, abstract, and keywords and decide that the paper did not fit our research objective. This reduced the subjectivity of article exclusion.

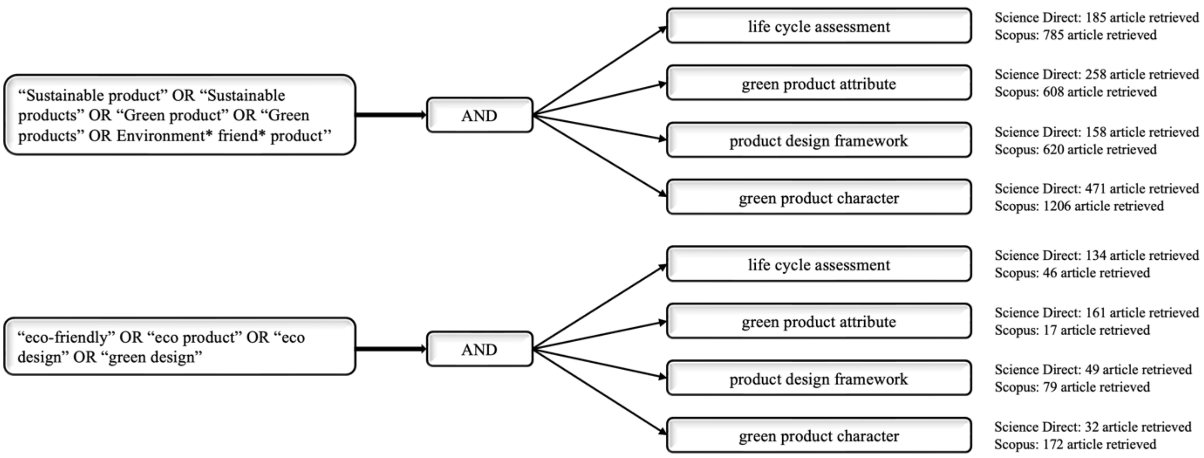

Figure 2: Query string combinations and quantity of articles retrieved.

Nonetheless, given the field's extensiveness, purposefully opted for a wide-reaching search algorithm, and leveraged the qualitative screening process conducted to select the relevant records that should be included in the synthetization. That is, decided to retrieve more articles in the searches and exclude them during the screening and reading steps of the PRISMA, rather than leaving them out. Inconsistencies on article inclusion were discussed to reach a consensus. As a result, 82 articles were included in the systematic literature review because they fit the inclusion criteria and the selection criterion (Moher et al., 2017) of addressing green product design attributes in their core. research and in their findings.

Regarding the quality of journals retrieved, all of them are Scopus or ScienceDirect indexed, which signals their publishing quality. Our analysis shows that the retrieved journals have an average 5.09 impact factor (SD = 2.660, Min = 0.542, Max = 10.302) on Clarivate's Journal Citation Reports. In Scopus, journals' average percentile classification was 79% (SD 21%, Min = 16%, Max = 99%) which demonstrates that on average, journals are highly ranked. These numbers indicate that the search algorithm retrieved papers from high quality journals. Fifty-six papers (out of the 82 retrieved) applied an exclusively quantitative approach, whereas five adopted a qualitative approach. Seven adopted a mixed methods approach and used both qualitative and quantitative approaches, whereas five papers did not clearly specify the method adopted. Figure 3 provides a synthesized systematic review flow diagram.

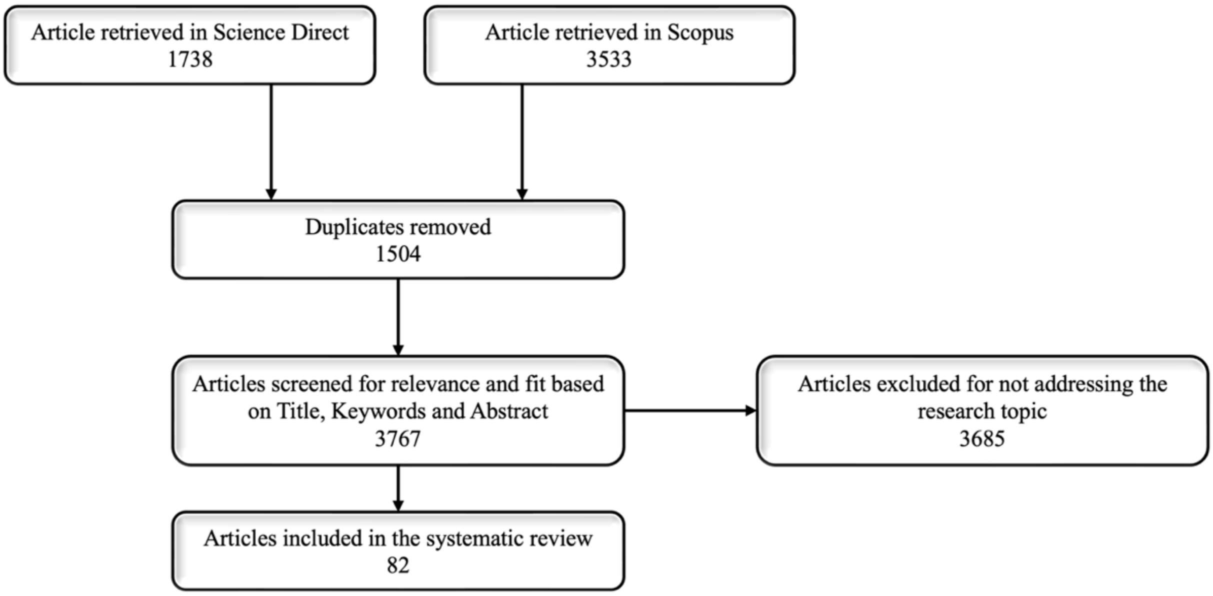

Figure 3: Synthesized systematic review flow diagram of the searches

3.2.3 Synthesisation and Reporting

As the last step of the (ii) execution and systematization phase, article reading and cataloguing was carried out with the assistance of a spreadsheet to extract relevant data (Moher et al., 2017). Finally, proceeded to the (iii) synthesisation and reporting phase, where reviewed all the articles selected, discussed their contributions, and synthesized the knowledge derived from the systematic review. For that, content analysis technique was used. Content analysis encompasses a set of communication analysis techniques (Bardin, 1977; Downe- Wamboldt, 1992). Thus, the content of the selected articles was classified based on the parameters defined a priority as being green product attributes (Bardin, 1977).

Therefore, the content analysis employed can be described as deductive, since based on the production, use, and end-of-life phases, the attributes are allocated and identified in the articles reviewed (Elo and Kyngäs, 2008). In total, approximately 470 green product attributes studied in the articles reviewed and the list of these attributes are shown in Table A1. Nevertheless, since the attributes were extracted in their original forms, the list comprised several repetitions and synonyms. Thus, repeated attributes were excluded and merged synonyms into one single attribute. Finally, a comprehensive list composed of 18 individual attributes were generated.

3.3 ATTRIBUTE SELECTION AND FINALIZATION

After implementing the PRISMA methodology to identify and extract 470 attributes which was further refined to 49 attributes(after removing synonyms and repetitions) relevant to green product design as shown in table 2, a systematic process was followed to refine this initial list into a final set of attributes. The Delphi method was employed to achieve expert consensus, and Percentage Agreement method was utilized to measure the agreement among experts at each stage.

Table 2: The list to 49 attributes.

Polymers	Elastomers	Plastic Additives	Metals
Assorted Natural Fibers	Biopolymers	Recycled Polymers	Recycled Metals
Composite Materials	Sustainable Wood	Polymers Processing	Metal Processing
Metal Casting	Additive Manufacturing	Subtractive Manufacturing	Chemical Treatment
Surface Coatings	Metal Finishing	Textile Manufacturing	Electrical
Renewable Energy Sources	Heat	Solar Energy Utilization	Energy Recovery
Fuel	Durability	Reusability	Cargo
Ergonomics	Performance Efficiency	User Safety	Public Transportation
Controlled Disposal	Open Air Disposal	Controlled Landfill	Open Pit Landfill
Material Recyclability	Waste Incineration	Composting	Carbon Footprint
Water Consumption	Energy Efficiency	Toxicity of By-products	Resource Scarcity Mitigation
Circular Economy Consideration	Biodiversity Preservation	Supply Chain Transparency	Packaging Sustainability
Ethical Sourcing			

3.3.1 Delphi Method

The Delphi method is an iterative process designed to collect and distil expert opinions through multiple rounds of structured feedback. It was chosen for its ability to achieve consensus among a group of experts on complex topics, such as identifying critical attributes for green product design framework.

First Round: Initial Ratings and Feedback

1. **Expert Selection:** Seven domain experts were selected based on their experience in sustainable product design, materials science, and life cycle assessment (LCA).
2. **Questionnaire Development:** A questionnaire containing the 49 refined attributes (after removing synonyms and repetitions) was shared with the experts. Each attribute was rated on a 1–5 Likert scale, where 1 indicated low relevance and 5 indicated high relevance shown in Table A2.
3. **Data Collection:** Experts provided their ratings independently to ensure unbiased responses.
4. **Percentage Agreement**
   To assess the level of consensus among the experts, the **Percentage Agreement** method was used. This approach involves calculating the percentage of experts who rated each

attribute as **4 (Very important)** or **5 (Extremely important)**, reflecting a higher level of agreement on the importance of each attribute.

Second Round: Reassessment Based on Group Feedback

1. **Feedback Summary:** A summary of the group's responses from Round 1, including average ratings and key themes, was provided to the experts.
2. **Re-evaluation:** Experts were asked to reassess their ratings, considering the group feedback. Attributes with significant rating variability or disagreement were discussed in detail.
3. **Statistical Analysis:** The same metrics (mean, SD, IQR, and Kendall's W) were recalculated. Improvements in Kendall's W indicated convergence toward consensus.

3.3.2 Calculation of Percentage Agreement

The **Percentage Agreement** for each attribute was calculated using the following formula:

$$\% \boldsymbol{Agreement} = \left(\frac{Number\ of\ Expert\ with\ ratings \geq 4}{Total\ number\ of\ Experts}\right) \times 100$$

For example, if an attribute received ratings of **4 or 5** from 4 out of 7 experts, the **Percentage Agreement** for that attribute would be:

$$\% \boldsymbol{Agreement} = \left(\frac{4}{7}\right) \times 100 = 57.14\%$$

This process was repeated for all 49 attributes, and the **Percentage Agreement** was calculated for each one. Attributes with higher **Percentage Agreement** values indicate stronger expert consensus regarding their importance for green product design.

Out of the **49 attributes**, **18 attributes** achieved a **Percentage Agreement ≥ 85%**, indicating strong expert consensus regarding their relevance for green product design framework. These 18 attributes were selected for inclusion in the final framework, as they reflect the collective expert judgment and align closely with sustainability goals.

3.3.3 Selected Attributes

The table 3 below shows the 18 attributes finalized through the Delphi process, with their corresponding Percentage Agreement values:

Table 3: Percentage Agreement values.

Attribute	Percentage Agreement (%)
Polymers	85.71%
Elastomers	100%
Plastic Additives	85.71%
Metals	100.00%
Assorted Materials	85.71%
Electronics	100.00%
Polymers Processing	100.00%
Metal Processing	100.00%
Metal Finishing	100.00%

Electrical	85.71%
Heat	85.71%
Fuel	100.00%
Cargo	100.00%
Public Transportation	100.00%
Controlled Disposal	100.00%
Open Air Disposal	100.00%
Controlled Landfill	100.00%
Open Pit Landfill	100.00%

The Delphi Method, combined with the **Percentage Agreement** technique, provided a rigorous and systematic approach for selecting the key attributes for green product design framework. The iterative rounds allowed for the refinement of expert opinions, resulting in a final set of attributes that have strong expert consensus and high relevance to sustainable design practices.

3.4 DATA COLLECTION

The data collection process for calculating carbon emissions at every phase of the product lifecycle was critical in developing the methodology. Carbon emission data was primarily sourced from the *OKALA Practitioner Guide*, a key resource offering single-figure impact values for materials and processes. Additionally, several other authoritative sources contributed to a robust dataset, including *Delft University* in the Netherlands, *Ecoinvent 2.2* from the Swiss Federal Institute for Technology, the *European Life Cycle Database* in Italy, *Franklin Associates* in the USA, *Orb Analysis for Design* in the USA, *PRé Consultants* in the Netherlands, and the *United States Life Cycle Inventory Database* from NREL. These resources provided comprehensive data on material and process impacts, ensuring the accuracy and reliability of carbon emission calculations across the entire product lifecycle.

To ensure the accuracy and consistency of the data, we gathered detailed information for each phase of the product lifecycle, including material extraction, manufacturing, transportation, usage, and end-of-life disposal. The Life Cycle Assessment (LCA) approach was employed to quantify the carbon emissions associated with each phase. This method allowed for a thorough analysis of the environmental impact, facilitating the identification of key areas for potential emission reductions.

For example, Table 4 provides a snapshot of the type of carbon emission data extracted from the OKALA Practitioner Guide. It lists various materials and processes along with their associated carbon emissions, measured in kilograms of CO_2 equivalent (kg CO_2 e). By applying these values, we could accurately assess the environmental impact at each stage of the product lifecycle. The use of such standardized data ensures that the carbon emission calculations are reliable and comparable across different products and design scenarios.

This comprehensive data collection process forms the foundation for the subsequent phases of the methodology, where strategies for reducing carbon emissions are developed and implemented.

This approach effectively ties the example table to the broader discussion in the data collection section, helping readers understand the practical application of the data in your research.

To illustrate the use of the OKALA Practitioner Guide in calculating carbon emissions, you can include a table in your thesis that shows example data from the guide. Here's how you could present it:

Table 4: Example Carbon Emission Data from OKALA Practitioner Guide.

Material/Process	**Carbon Emission (kg CO_2 e)**
Aluminum (primary production)	11.3
Steel (recycled)	0.8
Polypropylene (virgin resin)	1.9
Glass (recycled)	0.6
Injection Molding (plastic)	3.1
Transportation (truck, 1 km)	0.02
Electricity (grid average)	0.5 per kWh
End-of-Life (landfill)	0.04

CHAPTER 4:

STUDY OF GREEN PRODUCT DESIGN USING RECYCLED AND GREEN MATERIALS

4.1 ROLE OF GREEN MATERIALS AND PROCESSES IN ACHIEVING SUSTAINABLE DESIGN GOALS:

Green materials and processes play a vital role in achieving sustainable design goals by addressing various environmental and social concerns. Here are the key roles they play:

- **Resource Conservation:** By reducing the extraction of raw materials and encouraging the use of renewable resources, green products and processes aid in the conservation of natural resources. Sustainable design lessens the strain on scarce resources and aids in the preservation of ecosystems by deciding to use recycled, reused, or sustainably obtained materials (Horne, R. 2013)

- **Energy Efficiency:** Energy efficiency is improved by using green materials and manufacturing techniques throughout a product's life cycle. Materials and industrial techniques that conserve energy utilise less energy during production, transportation, and consumption. As a result, greenhouse gas emissions, energy use, and product carbon footprint are all decreased (Itoya, Emioshor 2012).

- **Waste Reduction and Circular Economy:** Waste reduction and the shift to a circular economy are made easier by using green products and techniques. Materials that are compostable, recyclable, or biodegradable support ethical waste management procedures. The requirement for virgin resources is decreased and the amount of waste transported to landfills is decreased by designing items with disassembly and recycling in mind (Hotta, Y., & Aoki-Suzuki, C., 2014).

- **Pollution Prevention:** Green materials and processes aim to minimize pollution throughout the product life cycle. By avoiding or reducing the use of toxic substances, sustainable design mitigates environmental pollution and associated health risks. Green manufacturing processes focus on minimizing emissions, effluents, and hazardous waste, thereby reducing the negative impact on ecosystems and human health (Fiksel, J. 2012).

- **Improved Indoor Environmental Quality:** Green materials enhance the quality of the interior environment by lowering the emission of volatile organic compounds (VOCs) and other dangerous contaminants. The outcome is a healthier indoor environment for residents, a reduction in health hazards, and an improvement in general wellness (Wu, F., et al. 2007).

- **Social Responsibility and Ethical Considerations:** Social responsibility and ethical considerations in product design are addressed through green materials and procedures. They support neighbourhood initiatives, encourage fair trade, and guarantee secure employment across the supply chain. Sustainable design helps create a society that is more just and equitable by taking the social effects of materials and processes into account (Desai, A., & Mital, A. 2020).

- **Consumer Awareness and Preference:** Green products and manufacturing practises are in line with rising customer knowledge of and preference for sustainable goods. Green materials and methods are included into product design to assist meet consumer demand for eco-friendly solutions as well as to improve brand reputation (Camilleri, M. A., et al., 2023).

- **Innovation and Market Opportunities:** Green technologies and procedures spur innovation and create new business prospects. They promote the creation of cutting-edge products, technologies, and production techniques that are more efficient and deliver better performance. Businesses may stand out from the competition, acquire a competitive edge, and satisfy the rising demand for sustainable goods by implementing sustainable design **(**Tello, S. F., & Yoon, E. 2008).

Sustainable design promotes a holistic approach that strikes a balance between environmental stewardship, resource efficiency, social responsibility, and commercial feasibility by using green materials and processes. It makes it possible to create goods that support a more resilient and sustainable future in addition to being aesthetically beautiful and functional.

4.2 GREEN MATERIALS FOR PRODUCT DESIGN:

Green materials are those that have little to no negative environmental effects at every stage of their life cycle, from extraction or production to disposal or recycling. These materials were chosen due to their environmental friendliness, resourcefulness, and sustainability. These green materials are frequently employed in product design:

- **Recycled Materials:** These components are created by processing waste from the post-consumer or post-industrial sectors. Examples include paper, glass, metals, and recycled plastics. Reusing materials lessens the need for new resources, conserves energy, and keeps waste out of landfills (Polyportis, A., et al., 2022).

- **Renewable Materials:** Natural resources that can be regenerated in a fair amount of time are the source of renewable materials. Examples include sustainable forestry practice-certified wood, bamboo, cork, hemp, and other materials. Comparing these materials to non-renewable counterparts, they have lower embodied energy and carbon emissions (Garvin., 2018).

- **Biodegradable and Compostable Materials:** Materials that degrade spontaneously into their component parts through biological processes have less of an environmental impact. Contrarily, compostable materials decompose into nutrient-rich compost when given the right circumstances. Examples include natural fibres like jute and sisal and bioplastics made from plant starches (Toketemu, 2018).

- **Low-impact and Non-toxic Materials:** These substances were picked because of their low toxicity and low environmental impact. They consist of non-toxic and solvent-free substitutes for traditional materials, low-VOC (volatile organic compound) paints and varnishes, and water-based adhesives and finishes (Vezzoli, & Manzini. 2008).

- **Sustainable Textiles:** Sustainable textiles are created utilising environmentally friendly methods using recycled or organic fibres. Organic cotton, hemp, linen, and recycled polyester are a few examples. Sustainable textiles encourage ethical sourcing, less water use, and use of fewer chemicals during production (Blackburn, R. S., 2009).

- **Energy-efficient Materials**: The design of products using these materials results in greater energy efficiency. For instance, energy-efficient insulation materials, such cellulose or insulation with recycled content, can reduce heat transmission and lower energy use in buildings. Solar panels and energy-efficient glass for windows also help to harness renewable energy (Arunkumar, 2019).

- **Cradle-to-Cradle Certified Materials:** Materials that have earned Cradle to Cradle (C2C) certification can be recycled or upcycled endlessly without suffering any quality loss. Their material health, material reutilization, usage of renewable energy, water stewardship, and social fairness are all taken into account while evaluating them. These components guarantee a closed-loop system in which waste is converted into useful resources (McDonough, W., & Braungart, M. 2010).

- **Lightweight and High-strength Materials:** Reduced material use and transportation energy are achieved by using lightweight, high-strength materials, such as engineered wood or modern composites. Lightweight materials can decrease the carbon footprint associated with product manufacturing and use and increase fuel economy in transportation (Thompson, M., & Thompson, R. 2013).

When selecting green materials, it is important to consider factors such as environmental impact, energy use, recyclability, durability, and end-of-life options. Integrating these green materials into product design promotes sustainable practices, reduces resource consumption, minimizes waste generation, and contributes to a more environmentally friendly and socially responsible approach to product development.

4.3 GREEN PROCESSES IN PRODUCT DEVELOPMENT:

Green processes in product development refer to sustainable and environmentally friendly procedures used during the stages of product design, manufacture, distribution, usage, and disposal (Sapuan, S. M., & Mansor, M. R. 2021). These procedures seek to limit waste production, resource consumption, and product adverse environmental effects. Here are some instances of green product development procedures:

- **Design for Sustainability**: Green techniques are employed, beginning with product design that prioritises sustainability. In order to do this, every phase of the product's life cycle must be considered, from material selection to end-of-life planning. Reducing resource use, improving energy efficiency, and promoting recyclable and reusable materials are all key components of design for sustainability (Sapuan, S. M., & Mansor, M. R. 2021).

- **Life Cycle Assessment (LCA):** LCA is a process for evaluating a product's environmental effects throughout the course of its life cycle. Designers and manufacturers can improve a product's sustainability performance by completing an LCA to identify areas with high environmental effect. LCA aids in calculating the environmental advantages of eco-friendly procedures and products (Klöpffer, W., & Grahl, B. 2014).

- **Lean Manufacturing:** The concepts of lean manufacturing encourage the effective use of resources, the elimination of waste, and the improvement of production procedures. It seeks to reduce inventory, stop non-value-added processes, and boost overall operational effectiveness. Product designers can cut down on wasteful energy use, pollution, and material waste by utilising lean manufacturing techniques (Bhamu, J., & Singh Sangwan, K. 2014).

- **Energy Efficiency and Conservation:** Enhancing energy efficiency during product manufacturing, operation, and consumption is the main goal of green processes. This include implementing energy-efficient technology, improving the way things are made, and creating goods that use less energy to accomplish what they're meant to. Green product creation also benefits from energy conservation practises include adopting energy-efficient components, putting in place smart controls, and encouraging energy-saving practises (Haines., et al, 2010).

- **Waste Reduction and Recycling:** Recycling and waste minimization are prioritised in green operations. This entails putting waste creation during manufacture into practise by using approaches like lean production and process optimisation. The recovery of valuable materials at the end of a product's life cycle is facilitated by designing goods for disassembly and recycling ability. Green processes are also supported by putting recycling programmes into place and employing recycled resources in manufacturing (Hotta, Y., & Aoki-Suzuki, C. 2014).

- **Supply Chain Optimization:** Environmental effects along the entire supply chain are taken into account in green procedures. This entails assessing and choosing suppliers based on their sustainability policies, cutting down on travel time, and encouraging ethical material sourcing. In the creation of green products, collaboration with suppliers to increase productivity and lessen environmental impacts is crucial (Mudgal, R. K., et al, 2009).

- **Water Conservation:** Throughout the product life cycle, green processes work to reduce water use. This entails incorporating water-saving practises and technologies into production procedures, promoting water-efficient product conceptions, and increasing user knowledge of water conservation (Johnston, A. 2014).

- **Stakeholder Engagement and Education:** To raise awareness and promote sustainable practises, green processes require including stakeholders like as employees, suppliers, customers, and regulatory organisations. The adoption of green procedures can be accelerated by offering training and information on sustainability, supporting responsible product use, and obtaining stakeholder feedback (Chen, D., et al, 2023).

Companies may lessen their environmental impact, increase operational effectiveness, adhere to regulations, satisfy customer expectations, and contribute to a more sustainable future by incorporating green methods in product development (Chen, D., et al, 2023). These procedures help to uphold the circular economy, resource conservation, and social responsibility tenets, ultimately resulting in the production of goods that are socially responsible, commercially viable, and environmentally benign.

4.4 CASE STUDIES AND BEST PRACTICES:

For the implementation of sustainable design strategies, case studies and best practises in the use of eco-friendly materials and production techniques in product creation can be a great source of knowledge and inspiration. Here are few instances:

- **Patagonia's Common Threads Initiative:** The Common Threads Initiative was started by the outdoor clothing manufacturer Patagonia to encourage a more environmentally friendly method of product design and usage as shown in figure 4. They offer a recycling programme for their apparel and encourage customers to fix, repurpose, and recycle their clothing. This effort highlights the value of creating durable products and offering end-of-life options to reduce waste (Rattalino, F. 2017).

Figure 4: Patagonia's common threads program (Vila, M., & Moya, S. 2023).

- **Interface's Mission Zero:** The Mission Zero programme was launched by Interface, a multinational manufacturer of modular flooring, with the objective of having no adverse environmental effects by the year 2020 as shown in figure 5. They switched to renewable energy sources, used sustainable products, and recycled and reused garbage to minimise it (Luqmani, A., et al, 2017). This case study demonstrates how environmentally friendly materials, waste minimization, and renewable energy can all be used to produce innovative products.

Figure 5: Interface's Mission Zero (Interface. 2022).

- **Tesla's Electric Vehicles:** Tesla transformed the car business by creating electric vehicles (EVs) with an emphasis on sustainability shown in figure 6. To cut down on energy use and pollution, their vehicles use eco-friendly components including lightweight composites and lithium-ion batteries (Wu, Z. Q., 2022). The success of Tesla serves as a testament to the ability of green products and methods to change industries and tackle environmental issues.

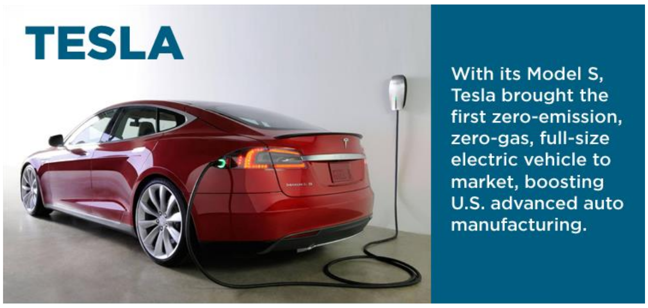

Figure 6: Tesla's Electric Vehicle environmental impact (Tesla, 2022)**.**

- **Nike's Considered Design:** Nike's Considered Design initiative seeks to lessen the negative effects of their products on the environment shown in figure 7. They use energy-efficient manufacturing techniques, sustainable materials, and creative manufacturing procedures to reduce waste. Nike's strategy highlights the significance of cooperating with suppliers to implement green practises and incorporating sustainability into the design process (Angeles, R. 2014).

Figure 7: Nike move to zero (Nike, 2022).

- **InterfaceFLOR's ReEntry Program:** The ReEntry programme was put in place by InterfaceFLOR, a well-known producer of modular carpet, to salvage and recycle carpet tiles as shown in figure 8. They gather used carpet tiles through this programme, sort the materials for recycling, and then repurpose them to create new goods. The circular economy concepts and the significance of designing items for disassembly and material recovery are both highlighted by the ReEntry programme (Marsh, A., & Khan, A. 2011).

Figure 8: InterfaceFLOR's ReEntry Program (Interface, 2023).

These case studies showcase instances of green product creation that used green materials and procedures successfully. They serve as examples of the advantageous effects that employing sustainable design principles may have on the environment and society. Companies may stimulate innovation and sustainability by studying these best practises so they can take inspiration from successful cases and apply them to their own product development procedures.

4.5 CHALLENGES AND LIMITATIONS:

Although using green materials and manufacturing techniques has many advantages for product design, there are also drawbacks and restrictions that must be taken into account. Here are some typical difficulties:

- **Limited Availability and High Costs:** Green materials, particularly those that are novel or are obtained sustainably, might not be widely available. Finding appropriate materials for their goods may become challenging for designers as a result. Additionally, green materials are frequently more expensive than conventional alternatives, which presents problems for organisations with limited budgets (Santos, et al, 2016).

- **Performance and Compatibility:** Green materials, particularly those that are novel or are obtained sustainably, might not be widely available. Finding appropriate materials for their goods may become challenging for designers as a result. Additionally, green materials are frequently more expensive than conventional alternatives, which presents problems for organisations with limited budgets (Hegab, H., et al, 2023).

- **Lack of Standardization and Certifications:** Accurately assessing and comparing the environmental impact of green products and processes can be difficult in the absence of standardised definitions, recommendations, and certifications. It becomes challenging to verify claims regarding the sustainability credentials of materials without precise criteria, which causes uncertainty in the marketplace (Knight, P., & Jenkins, J. O. 2009).

- **Complexity in Supply Chains:** Green materials can require intricate supply systems with numerous stakeholders. In terms of traceability, transparency, and assuring the sustainability of each stage of the supply chain, this complexity may provide difficulties. To meet these issues, cooperation and coordination between manufacturers, distributors, and suppliers are essential (Mudgal, R. K., 2009).

- **Trade-Offs and Trade-Down Effects:** Green materials might be better for the environment, but they might also compromise other sustainability factors. A material that is highly recyclable, for instance, might need more energy to produce. To prevent unforeseen negative effects, it is crucial to undertake a comprehensive analysis and take into account the whole life cycle implications of materials (Hegab, H., et al, 2023).

- **Consumer Perception and Acceptance:** Adoption of green products and processes is significantly influenced by consumer perception and acceptability. The functionality, appearance, or longevity of products manufactured from eco-friendly materials may worry some customers. To overcome these difficulties, consumers must be educated and made more aware of the value and advantages of sustainable products (Sharma, R., & pahuja, J. 2020).

- **Regulatory and Policy Landscape:** The adoption of green products and procedures may be impacted by the regulatory and policy environment. The widespread adoption of sustainable alternatives may be hampered by inconsistent legislation, a lack of incentives, or insufficient enforcement. For the shift to sustainable product design to be successful, governments and regulatory organisations must establish clear standards and frameworks (Chen, D., et al, 2023).

- **Continuous Innovation and Research:** Rapid innovation and research are required to overcome current constraints as green materials and processes develop. The availability, performance, and cost-effectiveness issues can be addressed with the aid of technological, material science, and sustainable manufacturing procedures (Romli, A., 2014).

Despite these obstacles, it is essential to consider sustainable product design as well as the use of eco-friendly materials and procedures. Stakeholders can strive to identify creative solutions and accelerate the shift to a more sustainable and circular economy by acknowledging and tackling these limits. To overcome these obstacles and realise the potential of green materials and processes in product creation, collaboration between designers, manufacturers, policymakers, and consumers is essential.

4.6 FUTURE DIRECTIONS AND RECOMMENDATIONS:

There are a number of potential future directions and suggestions to think about as the subject of green product design continues to develop:

- **Advancements in Green Materials:** Expanding the alternatives for sustainable product design will depend on ongoing research and development of green materials. The investigation of novel materials with enhanced environmental performance, such as biodegradable polymers, bio-based composites, and cutting-edge recycled materials, is part of this process. Innovation in this field can be boosted by funding material science research and working with suppliers (Sapuan, S. M., & Mansor, M. R. 2021).

- **Circular Economy Approaches:** The sustainability of product design can be considerably improved by adopting circular economy ideas. Reusing, repairing, and recycling materials while designing items will help cut down on waste and the need to mine new resources. Remanufacturing and product take-back programmes are two circular economy initiatives that can be integrated to create a more resource-efficient and circular economy (Wu, Z. Q., et al, 2022).

- **Digital Technologies and Virtual Design:** Utilising digital tools like virtual reality (VR) and computer-aided design (CAD) can speed up the product design process and make sustainability evaluations easier. With the help of these technologies, designers can explore different materials and production techniques, simulate environmental effects, and visualise and optimise product designs (Li, C., et al, 2023).

- **Emphasis on Social Sustainability:** Future green product design should prioritise social sustainability factors like ethical labour practises, worker safety, and social fairness in addition to environmental sustainability factors. More comprehensive and responsible design outcomes can be achieved by including social sustainability criteria into product development frameworks and working with suppliers to ensure ethical practises (Vila, M., & Moya, S. 2023).

- **Life Cycle Thinking Integration:** Processes for product design should be more linked with the use of life cycle thinking. This entails taking into account a product's whole life cycle, including any upstream and downstream effects. Sharing information and data on environmental consequences, working with supply chain partners, and completing thorough life cycle evaluations may all improve decision-making and advance sustainability along the value chain (Maxwell, D., & Sheate, W. 2006).

- **Education and Collaboration:** It is vital to encourage designers, engineers, and manufacturers to learn about and become aware of green product design. This includes educating designers on sustainable design principles, exchanging case studies and best practises, and encouraging cooperation between the academic community, business, and government agencies. Participating in industry-wide projects, alliances, and certifications can encourage action on sustainability issues Camilleri, (M. A., et al, 2023).

- **Policy and Regulatory Support:** Governments may significantly contribute to the promotion of green product design by enacting favourable laws and regulations. An enabling environment for the production of sustainable products can be created through promoting sustainable procurement practises, offering incentives for sustainable design, and enforcing standards and certifications (Galbreth, M. R., & Ghosh, B. 2012).

- **Consumer Engagement and Communication:** It is crucial to effectively communicate with consumers about the value of green products and their advantages to the environment. Consumers can make informed decisions with the use of transparent labelling, eco-labels, and product certifications. Demand for green products can be increased by engaging consumers through marketing initiatives, product education, and showcasing the advantages of sustainable design (Galbreth, M. R., & Ghosh, B. 2012).

In summary, ongoing innovation, teamwork, and the incorporation of sustainability concepts throughout all phases of product development are key to the future of green product design. The design industry can help create a future that is more robust and sustainable by embracing emerging technology, using circular economy strategies, emphasising social sustainability, and encouraging stakeholder engagement.

4.7 CONCLUSION:

In order to achieve sustainability, it is crucial that we understand green product design techniques and materials. We may produce goods that minimise their environmental impact, encourage social responsibility, and work towards a more sustainable future by incorporating sustainable concepts into the design process.

We have looked at the history and importance of green materials and processes, the definition and guiding principles of green product design, the significance of sustainability in product development, the role of green materials and processes in achieving sustainable design goals, specific green materials and processes, as well as the difficulties, constraints, and approaches to green product design throughout this research article.

Green materials offer an alternative to conventional materials, such as low-toxicity options, recycled materials, and renewable resources. Initiatives for waste reduction, recycling, and energy-efficient production are all examples of "green processes." These elements work together to promote sustainable design by lowering resource consumption, cutting waste production, and reducing environmental effects over the course of the product's lifecycle.

Additionally, we have provided case studies and best practises from organisations like Patagonia, Interface, Tesla, Nike, and InterfaceFLOR that show how green materials and procedures can be successfully integrated into product development. These cases offer as motivation and direction for businesses looking to use sustainable design principles.

We must, however, also acknowledge the difficulties and constraints that come with designing green products, including the scarcity and high cost of green materials, their poor performance and incompatibility, the absence of standards and certifications, the complexity of supply chains, consumer perception, and the regulatory environment. Collaboration, continual innovation, and a dedication to education and awareness are all necessary for overcoming these obstacles.

There are various topics in the future that demand consideration and care. The development of green product design will depend on advances in green materials, adoption of circular economy concepts, integration of social sustainability, exploitation of digital technologies, and encouragement of cooperation, education, and legislative support.

We can develop products that not only satisfy the requirements of the present but also assure a more sustainable and resilient future by implementing sustainable design concepts and practises. We can accelerate the shift to a greener and more sustainable society through the combined efforts of designers, engineers, manufacturers, policymakers, and consumers.

CHAPTER 5:

FLEXIBILITY, CONTROL, AND SENSITIVITY IN GREEN PRODUCT DESIGN

5.1 INTRODUCTION:

A thorough awareness of sustainability and environmental responsibility must inform product design in today's world of rapid change. Green considerations must now be incorporated into the first stage of product lifecycle design if we are to successfully address the urgent issues of climate change, resource depletion, and pollution (Smith & Yen, 2010). With a particular focus on implementing green limitations, this review paper investigates flexibility, control, and sensitivity.

The first stage of product lifecycle design is crucial in determining a product's environmental impact. The choice of materials, the manufacturing method, and the design of the product are only a few decisions that have a significant impact on the entire lifecycle (Klöpffer & Grahl, 2014). Designers can proactively spot chances to lower environmental footprints, reduce waste production, and improve overall sustainability by taking green restrictions into account from the beginning (Vezzoli & Manzini, 2008).

Designers need to understand the numerous aspects that affect environmental performance in order to successfully integrate green limitations. Regulations pertaining to waste management and emissions standards act as significant obstacles that must be overcome (Toketemu, 2018). To ensure a comprehensive approach to sustainability, factors including resource efficiency, carbon footprint, recyclability, and eco-design principles must also be thoroughly evaluated (Thompson & Thompson, 2013).

The ability to adapt and respond to shifting requirements, technology, and environmental restrictions is made possible by the core idea of flexibility in product design. Designers can future-proof their goods by including flexibility in the early design stages, which will allow them to accommodate changing rules, consumer preferences, and emerging sustainability practises. Because of their flexibility to adapt, manufacturers may continuously enhance the environmental performance of their products (Zhang et al., 2016).

Monitoring and regulating a product's environmental impact requires control systems. Designers can review and improve sustainability indicators with the help of life cycle assessment (LCA) and environmental management systems (EMS) (Donnelly et al., 2006). These technologies offer insightful information about a product's environmental problem areas and direct decision-making to improve its overall ecological performance.

Another useful tool that helps designers comprehend how variations and uncertainties affect product performance and environmental outcomes is sensitivity analysis. Designers can discover crucial parameters, weigh trade-offs, and reach well-informed conclusions that are in line with sustainable objectives by conducting sensitivity assessments. Sensitivity analysis aids in quantifying how design decisions affect resource use, emissions, and waste production, supporting the best possible design solutions (Beccali et al., 2010).

In this review article, we will look at research, approaches, and case studies that demonstrate how to include control, sensitivity, and flexibility into the early stages of product lifecycle design while taking environmental considerations into account illustrated below in figure 9. We can learn a lot about the actual implementation of these ideas and how they affect environmental performance, cost effectiveness, and customer happiness by looking at successful examples.

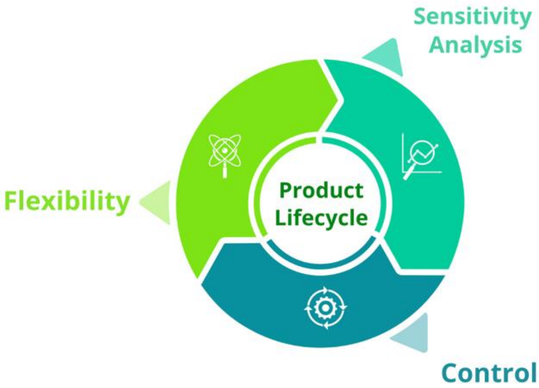

Figure 9: Accounting of Flexibility, Control and Sensitivity into early stage of Product Lifecycle.

However, there are difficulties and constraints in putting these ideas into practise, such as juggling competing goals, incorporating developing technologies, and handling tricky trade-offs. The examination of cutting-edge design tools, the incorporation of artificial intelligence, and the rise of new sustainability concepts—all of which could serve as directions for future research and development—will also be covered in this article. These topics will have an impact on how green products are developed in the future (Major, 2023).

8

Given below flowchart as shown in Figure 10, illustrates the key components and relationships involved in incorporating flexibility, control, and sensitivity in the early stages of product lifecycle design, with a focus on addressing green constraints and achieving sustainable outcomes.

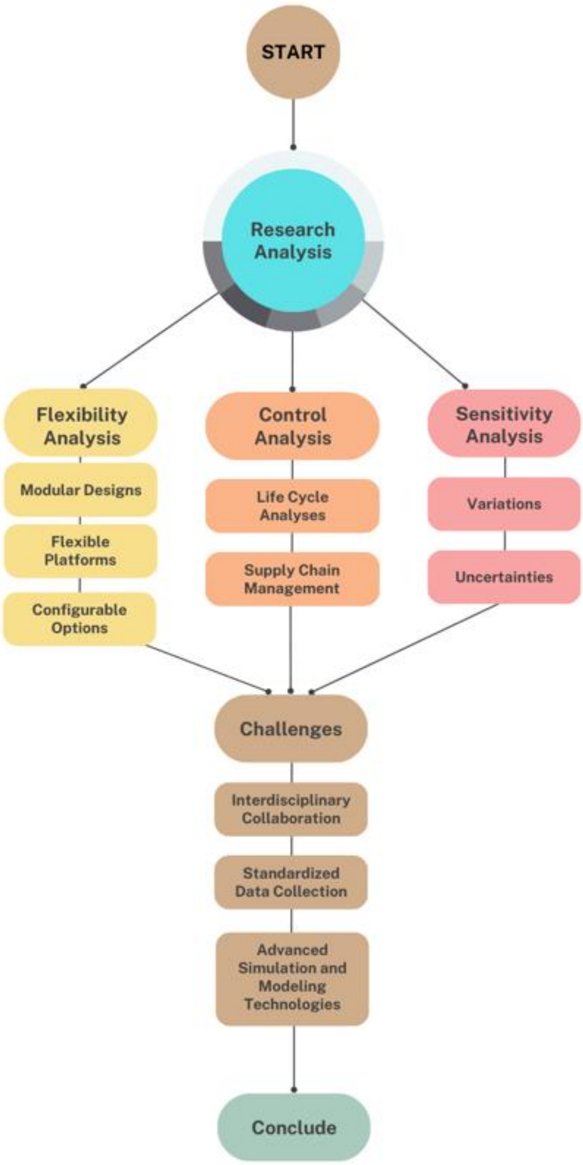

Figure 9: Flow Chart

This review aims to give researchers, practitioners, and policymakers a deeper understanding of the significance of integrating sustainability into product design by thoroughly examining flexibility, control, and sensitivity in the initial stage of product lifecycle design, with a specific focus on green constraints. By adhering to these principles, we may design goods that not only satisfy functional specifications but also reduce environmental impact, so promoting a more resilient and sustainable future.

5.2 LITERATURE REVIEW:

5.2.2 Understanding Green Constraints:

Designers need to be fully aware of the ecological restrictions that influence their design choices if they are to produce products that are environmentally sustainable. These limitations cover a wide variety of aspects of sustainability and environmental effect. Designers can successfully incorporate sustainability ideas and practises into their decision-making processes by taking these restrictions into account at the commencement of the product lifecycle design process. Let's examine some important green limitations in more detail:

- ***Regulatory Requirements:***
  The environmental performance of items is significantly shaped by regulatory regulations and standards. Emissions caps, rules governing energy efficiency, rules governing waste management, and limitations on the use of dangerous substances are a few examples of these. To ensure compliance and reduce environmental harm, designers must stay current on relevant rules and incorporate them into their product designs (Tran & Adomako, 2022).
- ***Resource Efficiency:***
  Utilising resources wisely is a crucial green restriction. Throughout a product's lifecycle, it entails optimising the use of materials, energy, and water. Designers should strive to minimise waste formation at all stages, from raw material extraction to end-of-life disposal, as well as to limit resource inputs and encourage circular economy principles (such as recycling and reusing materials) (Klöpffer & Grahl, 2014).
- ***Carbon Footprint:***
  It is crucial to reduce greenhouse gas emissions and combat climate change. The emissions produced over a product's full lifecycle, including the extraction of raw materials, manufacture, distribution, usage, and disposal, are included in its carbon footprint. To reduce the carbon footprint of their products, designers should take into account low-carbon substitutes, energy-efficient manufacturing techniques, and transportation strategies (Pertsova, 2007).
- ***Recyclability and Disposability:***
  Achieving a circular economy requires designing things to be easily recyclable and to be disposed of in a responsible manner. Designers can enable more effective recycling and lessen the environmental strain associated with waste disposal by using recyclable or biodegradable materials and including design features that make it easy to disassemble and separate components (Felton & Bird, 2007).
- ***Eco-Design Principles:***
  According to eco-design principles, a product's whole environmental impact must be taken into account. This entails taking the full lifecycle into account, lowering environmental risks, encouraging the use of sustainable materials, and reducing energy use. Designers must to strive to include eco-design principles in their decision-making, including eco-labeling, eco-packaging, and eco-marketing techniques (Maccioni et al., 2019).
- ***Life Cycle Thinking:***
  Assessing a product's environmental impact over the course of its whole life, from conception to disposal, is known as life cycle thinking. It takes into account a number of steps, including the extraction of raw materials, manufacture, distribution, usage, and end-of-life. Designers can identify and prioritise areas for improvement, optimise design decisions, and reduce the total environmental load associated with the product by embracing life cycle thinking (Mazzi, 2020).

Designers, engineers, environmental specialists, and stakeholders must work together and use a multidisciplinary approach to comprehend and incorporate these ecological restrictions into product design. By taking into account these limitations, designers can produce items that not only meet practical needs but also have a beneficial impact on environmental sustainability, in line with the larger objectives of building a greener and more sustainable future.

5.2.2 Flexibility in Product Design:
The ability of a product and the procedures that go along with it to adjust to and take into account changes in needs, technology, and environmental restrictions is referred to as flexibility in product design. It enables the effective integration of adjustments, enhancements, and customisation over the course of the product's lifecycle (Zhang et al., 2016). Here, we'll delve deeper into the idea of flexibility in product design:

- ***Adaptation to Changing Requirements:***
  Products are frequently impacted by changing consumer tastes, market demands, and legal restrictions. To ensure that the product can adapt to these changes, designers must account for flexibility and incorporate it into their designs. This might entail creating modular parts that are simple to upgrade or replace, looking into flexible alternative materials or manufacturing techniques, and utilising agile design methodologies to encourage incremental modifications (Bloch, 1995).
- ***Incorporating Emerging Technologies:***
  Rapid technological breakthroughs allow goods with flexible designs to easily incorporate new technologies. Designers can handle future technological advancements without necessitating a new redesign by building goods with modularity and compatibility in mind (Gerwin, 1993). This takes into account interoperability and standardisation to facilitate the seamless incorporation of new features, technologies, or upgrades.
- ***Future-Proofing:***
  It takes flexibility in product design to foresee potential problems down the road and create solutions. This involves taking into account prospective modifications to laws, environmental standards, or business practises (Rehman et al., 2017). Designers may future-proof their goods against obsolescence by introducing flexibility, ensuring that they stay applicable and ecologically responsible in the face of shifting market conditions.
- ***Modular Design:***
  A crucial component of product design flexibility is modularity. It entails breaking down a product into more manageable, interchangeable parts or modules that can be quickly changed or replaced. The effective customization, repair, and upgrade capabilities of modular design help to cut down on waste and increase product lifespan (Newcomb et al., 1996). Modular design also reduces downtime and costs by enabling effective repair and maintenance.
- ***Design for Manufacturing and Assembly (DFMA):***
  Flexibility of the final product is influenced by design considerations for production and assembly. Designers can increase flexibility by enabling quick and affordable production adjustments by taking into account manufacturing restrictions and using standardised components and procedures. To increase manufacturing techniques' agility in responding to shifts in demand or specifications, designers should concentrate on streamlining assembly procedures, lowering the number of parts, and optimising part counts (Molloy et al., 2012).
- ***User-Centered Design:***
  Incorporating flexibility also entails taking user preferences and demands into account. Designers can create goods that are easily customizable or personalised by comprehending the varied needs of users. This can entail adding customizable functions, flexible user interfaces, or programmable settings to accommodate unique user preferences without requiring significant alterations or redesigns (Toros, 2020).
- ***Design Validation and Testing:***

During the design phase, flexibility should be rigorously tested and analysed. Simulation and prototyping can be used to evaluate a product's performance in various settings and spot any potential problems with flexibility (Jaeckel, 1982). Designers may make sure the product satisfies the desired level of adaptability and performance by undertaking thorough validation.

Overall, including flexibility into product design makes it possible to adapt to changing needs, makes it easier to include cutting-edge technologies, decreases waste, and improves the product's overall sustainability. Designers may make goods that are easily adaptable to changing market dynamics, technical improvements, and environmental limits while still offering clients individualised and customised experiences by using a flexible design approach (Zhang et al., 2016).

5.2.3 Control in Product Design:
Control in product design refers to the construction of systems and strategies that allow designers to track, evaluate, and manage the environmental performance of goods over the course of their lifecycles. To ensure that sustainability goals and objectives are accomplished and upheld, systems and processes must be put in place. The following are significant components of control in product design:

- ***Life Cycle Assessment (LCA):***
  15 A common technique for assessing a product's environmental impact from the extraction of raw materials to its disposal at the end of its useful life is life cycle assessment. A detailed understanding of a product's environmental impact, including energy use, greenhouse gas emissions, resource depletion, and waste production, is provided through a life cycle assessment (LCA). Through LCA, designers can find opportunities for environmental improvement and make wise choices to improve the product's overall environmental performance (Klöpffer & Grahl, 2014).

- ***Environmental Management Systems (EMS):***
  Environmental management systems give product design and development processes a formal framework for managing and enhancing the environmental aspects of such processes. Guidelines and best practises for building an efficient EMS are provided by systems like ISO 14001 (Santos-Reyes & Lawlor-Wright, 2001). Designers can systematically identify, monitor, and manage environmental effects, define targets and goals for improvement, and continuously assess and optimise the environmental performance of the product by putting an EMS into practise.

- ***Design for Environment (DfE):***
  Design for Environment" is strategy that incorporates environmental factors into the creation of new products. It entails taking into account the effects on the environment of material choice, manufacturing procedures, energy consumption, waste production, and product disposal (DeMendonça & Baxter, 2001). Designers can proactively spot possibilities to reduce the product's environmental effect and raise its general sustainability by implementing DfE principles. This involves choosing eco-friendly materials, conserving energy, and creating products that can be disassembled and recycled.

- ***Supply Chain Management:***

In product design, control goes beyond the confines of the actual design process. The entire supply chain's environmental impact must be managed and under control. In order to use sustainable materials and processes, suppliers must follow environmental regulations, and transportation and logistics must be optimised to reduce carbon emissions (Mudgal et al., 2009). Designers and suppliers should work together to achieve these goals. Environmental concerns should be integrated into the production process as early as possible thanks to effective supply chain management.

- ***Performance Monitoring and Reporting:***
  Control in product design necessitates the development of performance measurements and indicators to track and assess the product's environmental performance over time. Data on energy use, emissions, trash production, and other pertinent parameters must be gathered in order to do this. Designers may improve a product's sustainability performance by constantly monitoring and analysing this data in order to spot trends, monitor development, and make data-driven decisions (Hertenstein & Platt, 2000). Consumers and stakeholders may benefit from transparent reporting of environmental performance.

- ***Continuous Improvement:***
  Control over product design demands a dedication to ongoing development. Designers can continuously improve the environmental performance of goods by actively soliciting feedback, participating in post-launch evaluations, and implementing lessons learned into subsequent design iterations. To keep the product at the forefront of sustainability, this entails keeping up with new technology, best practises, and legislative requirements (Sanchez & Mahoney, 1996).

Designers may manage and improve the environmental performance of their goods by including control systems into their designs. Designers may make sure that sustainability goals are accomplished and that the product contributes positively to environmental sustainability throughout its lifecycle by using LCA, EMS, DfE principles, supply chain management, performance monitoring, and continuous improvement.

5.2.4 Sensitivity Analysis in Product Design:
Sensitivity analysis is a technique used in product design to evaluate the effects of changes and uncertainties on a product's performance and environmental implications. It entails methodically examining how adjustments to design considerations, assumptions, or input variables impact the behaviour of the product and sustainability metrics (Maddulapalli et al., 2007). Key elements of sensitivity analysis in product design are listed below:

- ***Identifying Critical Parameters:***
  Sensitivity analysis aids designers in determining the most important factors or parameters that have a substantial impact on the product's performance and environmental impact. Designers can prioritise their efforts and concentrate on optimising the most important elements that have the greatest influence on sustainability indicators by evaluating the sensitivity of various design parameters, such as material qualities, dimensions, or process parameters (Sage, 1981).
- ***Evaluating Trade-Offs:***
  Making compromises between different design goals, such as performance, cost, and environmental effect, is a necessary part of product design. Using sensitivity analysis, designers can examine how changes in design parameters affect various performance

metrics and sustainability indicators to statistically evaluate these trade-offs (Hambali et al., 2009). This aids in recognising possible conflicts and discovering the best design solutions that achieve a balance between conflicting aims.

- ***Assessing Uncertainties:***
  Understanding the uncertainties related to the input variables and assumptions utilised in the design process is made easier through sensitivity analysis. Designers are able to pinpoint areas that require more investigation, testing, or data gathering in order to reduce uncertainty and increase the precision of design decisions by analysing how sensitive the performance of the product is to these uncertainties (Pianosi et al., 2016). This helps designers make better decisions, especially when dealing with insufficient or ambiguous information.
- ***Quantifying Environmental Impact:***
  Sensitivity analysis examines how changes in design parameters affect sustainability metrics like energy consumption, greenhouse gas emissions, water use, or waste creation in order to quantify the environmental impact of design decisions (Cellura et al., 2011). Designers can analyse many design possibilities, find the environmentally friendly solutions, and improve the product's overall environmental performance by measuring these effects.
- ***Optimization and Decision-Making:***
  Sensitivity analysis offers designers useful information for decision-making and optimisation. Designers can find design configurations that maximise desired outcomes or minimise undesirable effects by examining the sensitivity of the product's performance to various design parameters (Hopfe, 2009). Sensitivity analysis can be combined with optimisation algorithms to determine the best design solutions while accounting for various goals and restrictions.
- ***Design Validation and Robustness:***
  Sensitivity analysis aids designers in evaluating the dependability and robustness of design solutions. Designers might find possible weaknesses or sensitive regions by examining how changes in design parameters affect performance and sustainability metrics. With the help of this data, designers can make decisions that are resilient to variations and uncertainties, guaranteeing that the product will continue to work as intended and benefit the environment in the face of real-world challenges (Hopfe, 2009).
- ***Communicating Results and Uncertainties:***
  Designers have a way to express the ramifications and uncertainty related to design decisions thanks to sensitivity analysis. Designers may effectively explain the trade-offs, risks, and possibilities to stakeholders, decision-makers, and clients by measuring and visualising the sensitivity of design parameters and sustainability indicators (Hopfe, 2009). This encourages openness and makes it easier to have enlightened conversations about design choices and environmental trade-offs.

Understanding the impacts of variations and uncertainties on performance and environmental impact during product design is facilitated by sensitivity analysis. Sensitivity analysis allows designers to pinpoint key variables, weigh trade-offs, improve design options, and reach well-informed conclusions that are in line with long-term objectives. Sensitivity analysis ultimately helps create more durable, flexible, and ecologically friendly goods.

The graphical concept as shown in Figure 11 visually represents the interconnectedness and interdependence of flexibility, control, sensitivity analysis, and green constraints in the initial stage of product lifecycle design. It conveys the importance of considering and addressing environmental factors from the early stages of design to promote sustainable practices and minimize environmental impact.

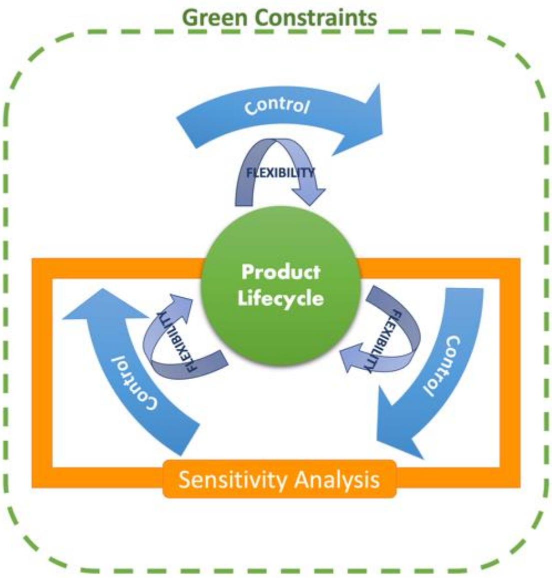

Figure 11: Illustrates the interconnectedness of flexibility, control, and sensitivity analysis in the context of product lifecycle design, with a specific emphasis on addressing green constraints.

The table 5 show below provides a concise comparison of these three aspects, highlighting their definitions, key components, purposes, importance, challenges, and future directions. This comparison can help readers understand the distinct features and contributions of flexibility, control, and sensitivity analysis in the initial stage of product lifecycle design, particularly with a focus on addressing green constraints and promoting environmental sustainability.

Table 5: The table provides a comparison of flexibility, control, and sensitivity analysis in the context of product lifecycle design

Aspect	Flexibility	Control	Sensitivity Analysis
Definition	The ability to adapt and modify design in response to changing needs or constraints	Monitoring and managing environmental impact throughout the product lifecycle.	Evaluating the impact of design parameters on environmental outcomes
Key Components	• Modular design • Customizable features • Upgradeability	• Supply chain management • Sustainable sourcing • Environmental standards and regulations	• Material selection • Energy consumption • Waste generation

Purpose	• Accommodate changing technologies • Meet evolving customer demands • Address environmental considerations	• Ensure compliance with regulations • Optimize environmental performance • Reduce environmental impact in production	• Minimize environmental footprints • Identify design optimization opportunities • Inform decision-making
Importance	• Enables market responsiveness • Facilitates product customization • Supports product upgradeability	• Ensures sustainable supply chain • Minimizes environmental risks • Promotes adherence to eco-standards	• Enhances sustainability of the product • Improves environmental performance • Drives continuous improvement

5.3 CASE STUDIES

In this section, two case studies that highlight the use of sensitivity, control, and flexibility in product lifecycle design with an emphasis on environmental considerations are presented. It demonstrates how these ideas contribute to environmental performance, cost effectiveness, and customer pleasure by highlighting exemplary examples of sustainable product design.

5.3.1 Case Study 1: Electric Vehicle (EV) Design

One product that needs to be carefully considered for flexibility, control, and sensitivity to environmental restrictions is electric automobiles.

- ***Flexibility:***
  Flexibility is essential in the design of electric vehicles to account for changes in battery technology and range needs. A top EV manufacturer created a flexible platform that made battery upgrades simple by using a modular design approach. As new and more effective batteries were available, this allowed consumers to improve their vehicle's battery capacity, boosting the range and performance without needing to replace the entire vehicle (Henriksen et al., 2021).

  Tesla's Model S as shown in figure 12 is a prime example of how electric vehicle (EV) architecture can be flexible. Customers were given the choice to select the battery option with the range that best suited their demands when the Model S was originally introduced. Customers had flexibility to choose the battery capacity that matched their budget and everyday driving needs thanks to the modular design approach. Tesla released updated battery options as battery technology developed, enabling current Model S owners to increase the battery capacity in their cars and hence increase range and performance without having to buy a new car (Lobo, 2020).

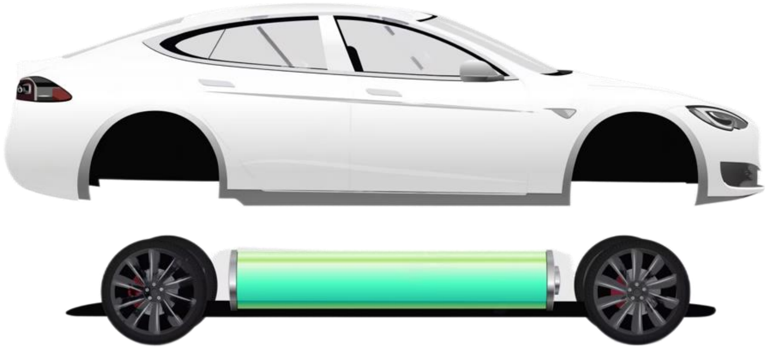

Figure 12: Tesla Model S (freepik.com)

- ***Control:***
  Complete control mechanisms were put in place to assure the environmental performance of electric vehicles. To identify and assess the environmental effects of various vehicle components and manufacturing processes, life cycle assessments (LCA) were carried out. The selection of materials and production processes that minimised environmental harm was guided by the LCA findings. Ensuring that suppliers followed sustainability standards and ethical sourcing procedures, strict control mechanisms were also built to monitor and manage the supply chain (Klöpffer & Grahl, 2014)..

  Tesla's cutting-edge software and firmware updates serve as a prime example of their approach to control in EV design as shown in figure 13. Tesla regularly provides over-the-air upgrades that optimise the vehicle's range and energy economy in addition to its performance. These updates give Tesla the ability to regulate and enhance a number of vehicle functionalities, including optimising regenerative braking, strengthening battery management algorithms, and increasing energy usage under varied driving circumstances. Even after their EVs have been sold, Tesla may continue to enhance the user experience and environmental performance of its vehicles by exerting control over their software and firmware (Zhou, 2023).

Figure 13: Tesla's cutting-edge software and firmware updates (Gurskiy, 2020).

- ***Sensitivity Analysis:***
  The design and performance of electric vehicles were greatly improved by the use of sensitivity analysis. To determine the effect of changes in variables like battery capacity, weight distribution, and aerodynamics on the vehicle's range and energy efficiency,

designers conducted sensitivity analyses (Więckowski et al., 2023). This study assisted in identifying the design elements that most significantly affected the vehicle's performance, allowing designers to adjust the design for maximum energy efficiency and range while still exceeding consumer expectations.

Consider the design optimisation efforts done by Chevrolet for their Bolt EV as shown in Figure 14, in the context of sensitivity analysis. Chevrolet carried out a thorough sensitivity analysis to see how different design considerations might affect the vehicle's range and energy efficiency. They looked at the sensitivity of variables like aerodynamics, weight distribution, tyre choice, and drivetrain efficiency to pinpoint the ones that had the biggest impact on the overall energy consumption and range of the vehicle. The Bolt EV's design was improved by Chevrolet's engineers in order to achieve optimum performance, maximise range, and reduce energy consumption, creating a more environmentally friendly and effective electric vehicle (Verma et al., 2023).

Figure 14: Chevrolet Bolt EV (Chevrolet, 2023)

These case studies highlight how flexibility, control, and sensitivity analysis help to develop environmentally friendly electric vehicles by demonstrating the ability to adapt battery capacities, the ability to control software updates, and the efforts to optimise design based on sensitivity analysis. These illustrations show how applying these concepts to EV design can improve user experience, performance, and long-term viability of electric transportation.

5.3.2 Case Study 2: Sustainable Packaging Design

- ***Flexibility:***
  Flexible packaging solutions were needed, according to a packaging design company, to fit shifting customer preferences and rising sustainability criteria. They created a modular packaging system that made it simple to customise and adjust. The system included reusable and replaceable parts, including lids, inserts, and dividers, which could be combined in different ways to suit the needs of diverse products (Connolly, 2007). This strategy made it unnecessary to use single-use packaging and made it easier to reuse and recycle packaging materials.

  The reusable packaging solution offered by Loop as shown in Figure 15 is an illustration of design versatility in sustainable packaging. To provide reusable packaging options for common products, Loop, a worldwide reuse network, collaborates with a number of consumer goods companies. The packaging system was created with versatility in mind, enabling customers to buy products in sturdy, reusable containers as opposed to conventional single-use packaging. After utilising the product, customers can send back the empty containers to Loop, where they are cleaned, sanitised, and refilled so that they are ready for reuse. This system's modular construction and flexibility reduce the amount of waste produced by single-use packaging while giving customers a practical and environmentally friendly choice (Baker, 2019).

Figure 15: Reusable packaging solution offered by Loop (Bronner, 2019).

- ***Control:***

  Throughout the packaging design process, the organisation used tight environmental control procedures. To track and control the environmental impact of their operations, they built an Environmental Management System (EMS) in accordance with ISO 14001 standards. The EMS made sure that environmentally friendly materials were used, such as recycled or biodegradable choices, and that manufacturing procedures were optimised to reduce energy use and waste production. They also actively engaged suppliers to ensure adherence to ethical sourcing and environmentally friendly production practises (Morrow & Rondinelli, 2002).

  The efforts of businesses like Patagonia provide as an example of the control part of sustainable package design as shown below in Figure 16. Manufacturer of outdoor apparel and equipment Patagonia has put in place strict control methods to guarantee the packaging's environmental performance. To make sure that the materials used in their packaging are in line with sustainability objectives, they carefully monitor and regulate the entire supply chain. To reduce its influence on the environment, Patagonia actively looks for environmentally friendly options, such as recycled materials or bio-based packaging, and adheres to strict design and manufacturing rules. Patagonia ensures that their products are supplied in packaging that complies with their stringent environmental standards by exercising control over their packaging decisions (Michel et al., 2019).

Figure 16: Patagonia sustainable package design (Strang, 2022).

- ***Sensitivity Analysis:***
  Sensitivity analysis was used to assess how various design and material options will affect the environment. In order to evaluate the sustainability of packaging options, the company performed life cycle analyses (LCAs), taking into account elements including material source, energy usage, carbon emissions, and end-of-life disposal. Sensitivity analysis made it possible to pinpoint design considerations and material selections that significantly affected the product's environmental effect. This gave the business the information it needed to choose design options and make decisions that would have the least negative effects on the environment overall while still satisfying functional and aesthetic demands (Boesen et al., 2019).

  An impressive illustration of sensitivity analysis in sustainable packaging design is provided by a beverage firm aiming to lessen the environmental impact of their packaging as shown in figure 17. The business performed a sensitivity study to determine the effects of several packaging characteristics, including material choice, size, and weight, on their carbon emissions and trash output. The company was able to determine which aspects had the greatest influence on how well they performed in terms of the environment by assessing the sensitivity of these criteria. They revised their packaging based on the study to employ lighter-weight materials, lower overall size, and optimise packaging dimensions, leading to significant savings in carbon emissions and waste throughout the product lifespan (Saleh, 2016).

Figure 17: Sustainable packaging design provided by a beverage firm (Eagle, 2017)

The aforementioned examples show how sensitivity analysis, flexibility, and control may be used to create sustainable packaging. Companies can create packaging solutions that minimise waste, reduce environmental impact, and offer consumers more sustainable options by implementing flexible packaging systems, exercising control over material selections and manufacturing processes, and performing sensitivity analysis to optimise design parameters. In order to attain a more circular and ecologically sensitive approach to packaging, these case studies emphasise the significance of incorporating these ideas into packaging design.

5.4 CHALLENGES AND FUTURE DIRECTIONS

Designing products with environmental considerations presents several difficulties. The challenges and restrictions encountered when implementing flexibility, control, and sensitivity from the outset of product lifecycle design are covered in this section. Additionally, it offers possible directions for future study, such as the creation of sophisticated design tools, incorporation of artificial intelligence, and investigation of cutting-edge sustainability ideas.

5.4.1 Challenges:

- ***Integration of Green Constraints:***
The efficient integration of environmental constraints across the whole design process is one of the major problems in product lifecycle design. This calls for a thorough awareness of environmental factors, sustainability criteria, and legal obligations. Designers must strike a balance between a number of factors, including performance, cost, and environmental impact, all the while adhering to changing environmental regulations. Interdisciplinary cooperation, ongoing learning, and the use of holistic design strategies are required to overcome this obstacle. (Ameri & Dutta, 2005)

- ***Data Availability and Quality:***
Effective sensitivity analyses, life cycle analyses, and environmental performance evaluations require accurate and trustworthy data. It can be difficult to locate full data on material characteristics, production procedures, supply chain management, and environmental effects. The precision of analysis and decision-making can be impacted by data gaps, inconsistencies, and differences in data quality. To meet this challenge, industry, academia, and regulatory agencies must work together to increase data collecting, standardisation, and transparency (Forcina et al., 2023).

- ***Complexity and Trade-Offs:***
Complex trade-offs between a variety of design restrictions and objectives are necessary in product design. Compromises and trade-offs are frequently necessary to achieve a balance between performance, cost, aesthetics, user experience, and environmental impact. Designers must handle these difficulties and take the long view when making judgements. Effective communication and decision-making frameworks that take into account the multifaceted character of sustainability are also required for this (Bate, 2008).

5.4.2 Future Directions:

- ***Advanced Simulation and Modeling:***
The creation and use of sophisticated simulation and modelling technologies will determine the direction of product lifecycle design in the future. These technologies can help designers conduct virtual testing, optimise design setups, and more accurately forecast how items will behave in the environment. The capabilities of these technologies can be improved by incorporating artificial intelligence, machine learning, and predictive analytics, enabling quicker and more informed decision-making (Morrison et al., 2017).

- ***Circular Economy Design:***
Future product lifecycle design should adhere to the concepts of the circular economy as sustainability and resource efficiency become more important. Designers should concentrate on producing goods that are robust, re-usable, recyclable, and made of materials that are simple to recover and incorporate into new items. A more circular and sustainable economy can be achieved by design principles like designing for disassembly, incorporating remanufacturing, and supporting sharing or leasing models (Cayzer et al., 2017).

- ***Digital Twin Technology:***
  The creation of a virtual copy of a real system or product using digital twin technology has the potential to improve product lifecycle design. Designers may track and improve a product's performance in real-time, pinpoint areas for development, and simulate various scenarios to determine the environmental impact of design modifications by fusing the physical and digital worlds. Throughout the duration of the product, digital twins can facilitate ongoing optimisation, preventative maintenance, and real-time decision-making (Tao et al., 2017).

- ***Stakeholder Engagement and Transparency:***
  Stakeholder involvement and openness should be prioritised in the design of future product lifecycles. Customers, suppliers, regulators, and other stakeholders can be included in the design process to help identify different points of view, gather insightful data, and promote a sense of shared accountability. Building trust, facilitating informed decision-making, and encouraging the adoption of sustainable products can all be achieved through open reporting of environmental performance and adherence to sustainability standards (Watson et al., 2017).

- ***Education and Collaboration:***
  Ongoing learning, teamwork, and information exchange are essential to addressing the issues and advancing product lifecycle design in the future. Through ongoing learning and professional development, designers should stay current on new technology, best practises, and legislative changes. The establishment of guidelines and standards for sustainable product design can be facilitated through cooperation between academia, industry, governments, and non-profit organisations (Watkins et al., 2021).

By addressing these issues and embracing new ideas, product lifecycle design can develop further and help create a more resilient and sustainable future where products are flexible, environmental impact is minimised, and sensitivity analysis is used to optimise them to meet environmental standards.

5.5 CONCLUSION

In conclusion, research on flexibility, control, and sensitivity analysis throughout the early stages of product lifecycle design offers helpful perspectives and strategies for dealing with environmental restrictions and supporting sustainable practises. Designers can build products that are versatile, ecologically friendly, and sensitive to changing market needs and regulatory constraints by incorporating these ideas into the design process.

Flexibility enables items to be adjusted to evolving technologies, consumer wants, and environmental factors. Designers can utilise elements that enable upgrades, repairs, and reuse, decreasing waste and extending product lifecycles, such as modular designs, flexible platforms, and configurable options.

Control mechanisms use methods and procedures to track, evaluate, and manage the environmental performance of products to guarantee that sustainability objectives are reached. In order to reduce environmental consequences and ensure ethical sourcing and manufacturing, environmental management systems, life cycle analyses, and supply chain management are necessary.

Sensitivity analysis aids designers in determining how variations and uncertainties affect the performance of their products and the effects they have on the environment. Designers can identify crucial elements, weigh trade-offs, and optimise design solutions to reduce environmental footprints and maximise sustainability by assessing the sensitivity of design parameters and performing life cycle evaluations.

However, difficulties still exist, including integrating environmental restrictions, managing complicated trade-offs, and ensuring data availability and quality. Interdisciplinary cooperation, greater data collection and standardisation, and cutting-edge simulation and modelling technologies are required to overcome these obstacles.

Future directions for product lifecycle design include adopting circular economy ideas, utilising digital twin technologies, encouraging stakeholder participation and transparency, and encouraging cooperation and education. Product lifecycle design may advance and help create a future that is more robust and sustainable by following these new pathways.

CHAPTER 6:

DEVELOPMENT OF A FRAMEWORK FOR GREEN PRODUCT DESIGN

6.1 IDENTIFICATION OF KEY PRINCIPLES:

This section introduces the key principles for the green product design (GPD) framework based on a review of the literature. The framework groups green product design attributes into categories across different lifecycle phases, drawing on similar categorizations in the works of Dangelico and Pontrandolfo (2010), Stark (2016), Paton and Andrew (2019), and Aydin and Badurdeen (2019).

The adaptation of the manufacturing, use, and end-of-life phases for product life cycle based on previous literature and adaptations of the works of Dangelico and Pontrandolfo (2010), Stark (2016), Paton and Andrew (2019), and Aydin and Badurdeen (2019). More specifically, the categorization is similar to the one adopted in Dangelico and Pontrandolfo (2010), which categorizes product lifecycle into "before usage", "usage", and "after usage" to map green practices that designers can implement to develop green product.

It is found that green attributes referring to the manufacturing phase are related to the design efforts in the manufacturing processes, product assembly, and other aspects of material efficiency, and operations' sustainability. Whereas, in the use phase, green attributes are related to how sustainability is delivered during the consumption of the product. Finally, the end-of-life phase encompasses design efforts related to product disassembly, reuse, recycle, biodegradability, etc. That is, the end-of life phase is related to the sustainability of product after used them

6.1.1 Manufacturing Phase of Proposed Framework

The manufacturing phase comprehends attributes related to manufacturing processes, packaging, logistics and it embraces 14 individual attributes divided into 4 attribute groups.

- The first group in this phase concerns materials. In this group, attributes are related to selection of materials that focus on increasing environmental sustainability by selection suitable materials.
- The second group in this phase concerns processes. In this group, attributes are related to selection of manufacturing process that focus on increasing environmental sustainability by selection suitable manufacturing processes.
- The third group in this phase concerns energy. In this group, attributes are related to selection of energy used during the manufacturing that focus on increasing environmental sustainability by selection suitable source of energy.
- The fourth group in this phase is concerns logistics. In this group, attributes are related to selection of mode of transportation that focus on increasing the environmental sustainability by selection of proper transportation.

6.1.2 Use Phase of Proposed Framework

The use phase comprehends attributes related to the usage of product and it embraces 3 individual attributes divided into 2 attribute groups.

- The first group in this phase concerns energy during use. In this group, attributes are related to selection of type of energy product works that focus on increasing environmental sustainability during use.
- The second group in this phase concerns replacements during use. In this group, the replacement is work as new product itself.

6.1.3 End-of-Life Phase of Proposed Framework

The End-of-life phase comprehends attributes related to the after-consumption stage of product and it embraces 4 individual attributes divided into 4 attribute groups.

- The first group in this phase concerns recyclability of the product after use. In this group the product which going to be recycle is treated as another product.
- The second group in this phase concerns reuse of the product. In this group the product which going to be reuse is also treated as another product.
- The third group in this phase concerns incineration of the product. In this group the incineration product is divided into controlled and open-air type incineration.

The fourth group in this phase concerns landfill of the product. In this group the landfill of the product is divided into controlled and open pit type landfill.

As design plays a central role in green product development and is responsible for adding sustainability to products in all life cycle phases (Fuller and Ottman, 2004), this aspect design was placed in the core of the framework as shown in Figure 3. This contributes to conveying design's omnipresence in green product design. It is decided to not include findings from articles that aimed to rank the most relevant attributes (such as de Medeiros et al., 2016; de Medeiros and Ribeiro, 2017; Diego-Mas et al., 2016, among others) since they tend to be context-specific and, thus, they would not adhere to the purpose of providing a more general mapping of designing a green product. Although some individual attributes or groups may be related to more than one phase, the aim is to provide a comprehensive list reflecting green product design attributes' dominant orientations. Specially because attributes may be of different importance for different products, and, therefore, adaptations may be necessary when a designer, researcher or practitioner decides to study or apply the framework to one specific product or industry.

6.2 INTEGRATION OF FRAMEWORK COMPONENTS

In this section, the framework components are grouped into attribute categories for each phase, aiming for a comprehensive and generalizable model suitable for diverse product types.

6.2.1 Manufacturing Phase Components

The production phase encompasses attributes within four main categories: materials, processes, energy, and logistics.

- **Materials:** Selection focuses on environmentally sustainable raw materials.
- **Processes:** Involves choosing eco-friendly manufacturing techniques.
- **Energy:** Considers renewable or low-impact energy sources in production.
- **Logistics:** Focuses on sustainable transportation methods to minimize environmental impacts.

6.2.2 Use Phase Components

The use phase includes three attributes divided into two categories.

- **Energy during Use:** Addresses energy type used to enhance sustainability.

- **Replacements:** Refers to components that may require replacement, prolonging product life and reducing waste.

6.2.3 End-of-Life Phase Components

The end-of-life phase covers four attributes within four categories: recyclability, reuse, incineration, and landfill.

- **Recyclability:** Ensures the product can be recycled efficiently.
- **Reuse:** Promotes the reusability of products or components.
- **Incineration:** Controlled vs. open-air incineration for waste management.
- **Landfill:** Emphasizes controlled landfilling to reduce environmental harm.

6.3 PROPOSED FRAMEWORK FOR GPD IMPLEMENTATION

This section provides a visual representation and detailed explanation of the GPD framework, focusing on the application of identified principles in the manufacturing, use, and end-of-life phases. Each attribute group reflects dominant orientations in green product design to guide designers, researchers, and practitioners in integrating these principles into specific products or industries.

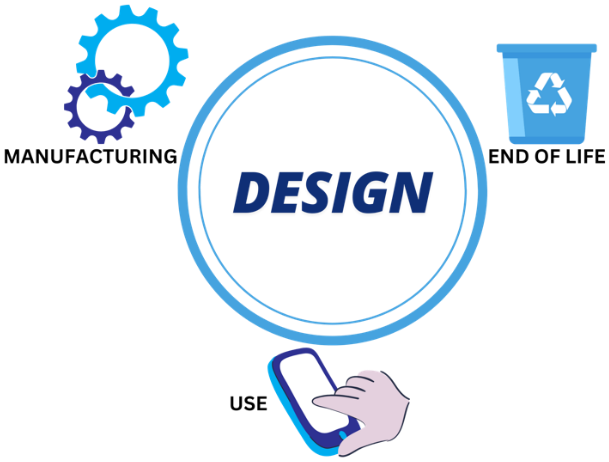

Figure 18: Proposed framework concept.

Figures 18 and 19 illustrate the proposed framework and its graphical representation, respectively. This structured approach will support designers in making informed decisions for environmentally responsible product development, ensuring sustainability across the entire product lifecycle.

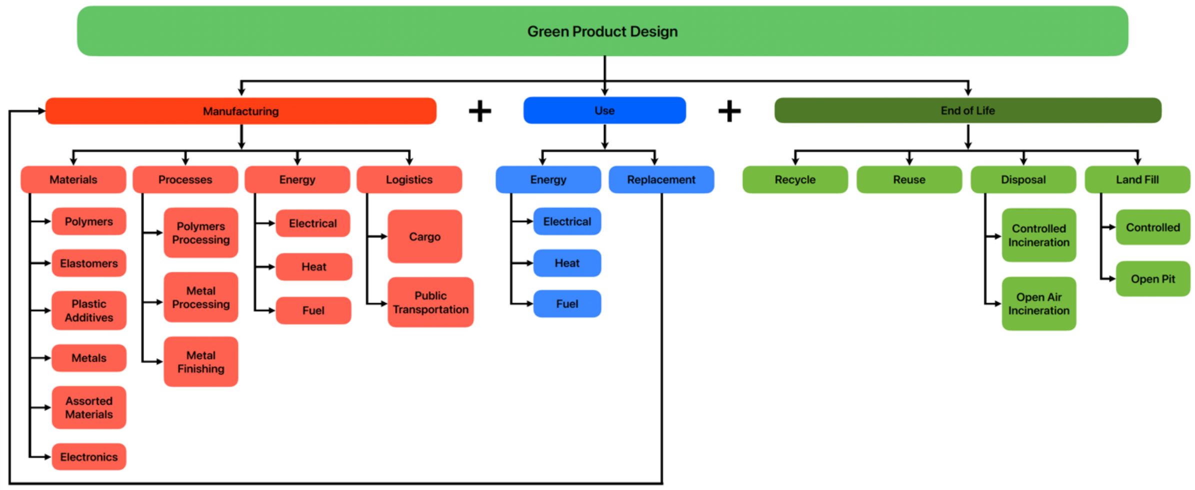

Figure 19: graphical representation of proposed Framework

6.4 CONCLUSION:

This chapter presented a comprehensive framework for green product design (GPD), structured to guide designers, researchers, and practitioners in embedding sustainability throughout a product's lifecycle. Drawing from established literature and adapting categorization approaches, the framework divides the product lifecycle into three main phases: Production, Use, and End-of-Life. Each phase encompasses distinct attribute groups, targeting critical areas where sustainability efforts can be maximized—ranging from material selection and energy use in production to recyclability and reuse at the end of a product's life.

The Production phase emphasizes eco-friendly material and process selection, sustainable energy sources, and efficient logistics, setting the foundation for environmental responsibility from the outset. The Use phase addresses sustainability during product consumption, particularly through energy efficiency and the minimization of replacement needs. The End-of-Life phase ensures environmentally sound disposal or reuse options, reducing the ecological footprint through recyclability, controlled incineration, and responsible landfilling.

By centralizing design as the core enabler of green product development, this framework provides a holistic approach that reflects design's role in ensuring sustainability across all phases of the product lifecycle. It also acknowledges the varying relevance of attributes based on product types, allowing for flexibility and adaptability in application.

In conclusion, this framework offers a structured and generalizable roadmap for green product design, applicable across diverse industries and product categories. It empowers designers to make informed, sustainable choices, paving the way for products that align with environmental objectives.

CHAPTER 7:

PRACTICAL AND EFFICIENT APPROACH FOR GREEN PRODUCT DESIGN

7.1 INTRODUCTION

The pursuit of green product design necessitates the integration of environmental considerations into the product lifecycle, from ideation to disposal. This chapter aims to elucidate a practical and efficient approach for implementing the proposed framework for green product design. By providing a concrete example, it demonstrate how the framework can be effectively applied in real-world scenarios, ensuring that green principles are not only theoretical but also actionable.

7.2 FRAMEWORK OVERVIEW

The proposed GPD framework divided into three stages of a product life cycle (manufacturing, use and end of life) as shown in figure 20, which provide carbon emission value at every stage of product life cycle, lower the carbon emission greener the product.

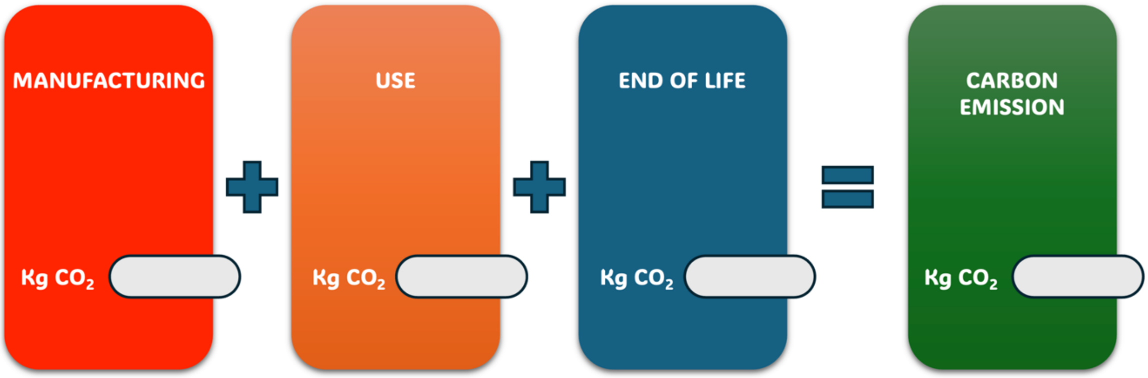

Figure 20: Proposed Green Product Design Framework

3 The proposed framework is a single-figure score LCA factors, which are considerably faster and easier to use than multiple-category LCA. This ease-of-use means that framework can be simply performed, with pencil and paper. Designers who use this method become familiar with the data to a degree that significantly informs their design work.

3 This framework can be use in many ways to understand the environmental performance of a design concept, ranging from fast initial screening to full product system analysis. Different approaches may be helpful, depending on the situation and the kinds of questions that the
3 designer is trying to answer. Three basic approaches to using this framework are simple screening, subassembly comparison, and complete system LCA. If two or more alternatives are available to compare, any of these approaches can be instructive.

To perform LCA of any product by using this proposed framework, following steps are involve:

Step 1. Define lifetime, functional unit, and boundary.
Step 2. Make bill-of-materials.
Step 3. Calculate estimated impacts.

Equation for calculation of carbon emission impact is given below:

Carbon Emission Impact = Amount of material utilized (kg) x Carbon emission value per kg.

For better understanding the following example shows how to perform complete LCA, the impact of two different tables of same size (i.e. H= 75cm, L= 80cm & W= 50cm approximately) is compared:

7.3 EXAMPLE OF COMPLETE SYSTEM LCA:

Table A

Table B

Figure 21: Two different Tables A and B respectively.

Comparing the impacts of two tables as shown in Figure 21. Table A is made from primary (virgin) polypropylene and primary steel and table B is similar but is made from secondary (recycle) polypropylene and secondary steel.

Step 1. Define lifetime, functional unit, and boundary

It is assumed that both the tables deliver 7200 hours of service. The functional unit is hour of use. The cardboard packaging of each table is recycled after delivery.

Table A		**Table B**	
Lifetime A	600 hours/year X 12years = 7,200 hours	Lifetime B	600 hours/year X 12years = 7,200 hours
Functional Unit	Impacts/hour	Functional Unit	Impacts/hour
System boundary	Excludes cleaning during use	System boundary	Excludes cleaning during use

Step 2. Make bill-of-materials

Materials	Primary PP	4.3kg	Materials	Primary PP	4.3kg
	Steel legs and fasteners	5.6kg		Steel legs and fasteners	5.6kg
	Corrugated cardboard	4.6kg		Corrugated cardboard	4.6kg
Manufacturing	Injection mold PP	4.3kg	Manufacturing	Injection mold PP	4.3kg
	Extrude steel	3.6kg		Extrude steel	3.6kg
	Nickel plate on steel	112m^2		Nickel plate on steel	112m^2
Transport	Truck	7.6ton-mi	Transport	Truck	7.6ton-mi

Disposal	landfill	Disposal	landfill

Step 3. Calculate estimated impacts

Input	Amount	* CO_2 eq. = *(kg)*	Impact *(kg)*	Input	Amount	* CO_2 eq. = *(kg)*	Impact *(kg)*
PP primary	4.3kg	1.68	7.22	PP sec	4.3kg	1.406	6.046
Inj. mold PP	4.3kg	0.59	2.537	Inj. mold PP	4.3kg	0.59	2.537
Steel primary	3.6kg	0.907	3.265	Steel sec	3.6kg	1.406	5.062
Extrude steel	3.6kg	0.19	0.684	Extrude steel	3.6kg	0.19	0.684
Nickel plate	$112m^2$	0.349	39.088	Nickel plate	$112m^2$	0.349	39.088
Truck 28t	7.6t.mi	0.199	1.5124	Truck 28t	7.6t.mi	0.199	1.5124
Landfill PP	4.3kg	0.045	0.1935	Landfill PP	4.3kg	0.045	0.1935
Landfill steel	3.6kg	0.0063	0.0226	Landfill steel	3.6kg	0.0063	0.0226

Total impact/life Table A: 54.52 kg co_2 eq. **Total impact/life Table B: 55.14 kg co_2 eq.**

Note: The process is only accurate to 2 significant figures, so we calculate the impacts per functional unit and round to two significant figures.

7.4 VALIDATION OF THE FRAMEWORK VIA CASE STUDIES

In this section, two case studies are presented to demonstrate the application of the newly developed green product design framework. These case studies were conducted to evaluate the environmental impact of different products using the Life Cycle Assessment (LCA) approach, integrated with the green product design principles outlined in the framework.

7.4.1 Case Study 1: Evaluating the Environmental Impact of a Bicycle

In this case study, the LCA of bicycle production in Bangladesh was conducted using ISO14040. This section discusses goal and scope of the proposed novel GPD framework's, life-cycle inventory, and life-cycle effect assessment method. Also discussed are the study's presumptions and the sources of the inventory data. The ISO standard states that an LCA study entails the following four steps: definition of the objective and scope, compilation of the life-cycle inventory, life-cycle assessment, and interpretation of the results (ISO 2006).

The scope, functional unit, and system boundaries must all be explicitly established at the outset during the life cycle assessment. The next step is to compile an inventory of the materials and energy utilized during each phase of the life cycle. The impact assessment is then completed using this data to calculate various environmental effects, which is the potential for global warming.

To achieve the goal of this study, the following steps have been followed:

a. Information Collection From previous publication for collection of life cycle inventories.
b. Define and use of Proposed GPD Framework for life cycle assessment of bicycle.
c. Data Validation and analysis

Information Collected From previous publication:

- The Bangladesh bicycle industry agreed to provide information and interviews, so these were the sources for the bicycle-related data used in this study (Papon R et al., 2019).
- Furthermore, The largest producer and exporter of bicycles in Bangladesh, this industry accounts for the majority of this sector. It has 12 interconnected depot and 3 manufacturing stations for mass production of pedal-cycles (Group M, 2018).
- The authority had data on the parts and production of the reference bicycle. Inventory data for bicycle production were gathered through questionnaires and interviews (Papon R et al., 2019).
- The reference bicycle's weight was precisely measured for all of its parts and components. To calculate the transportation distance, secondary sources were used.
- Additionally, secondary data were gathered from a variety of literature sources, such as reports, online resources, earlier published articles, and Ecoinvent 3.5 (Ecoinvent, 2018).

Figure 22 shows the system boundary of the Bangladeshi bicycle industry's LCA study (Papon R, et al., 2019). The Eco Invent 3.4 database was used to obtain baseline data for the processing of raw materials (such as metal, rubber, plastic, and other materials) as well as raw materials from the environment, including inputs from the Technosphere, needed for the manufacture of bicycles (Ecoinvent, 2018).

Tables 6 and 7 demonstrate the material specifications for bicycle production in Bangladesh, as well as the components needed during use for entire life cycle, respectively.

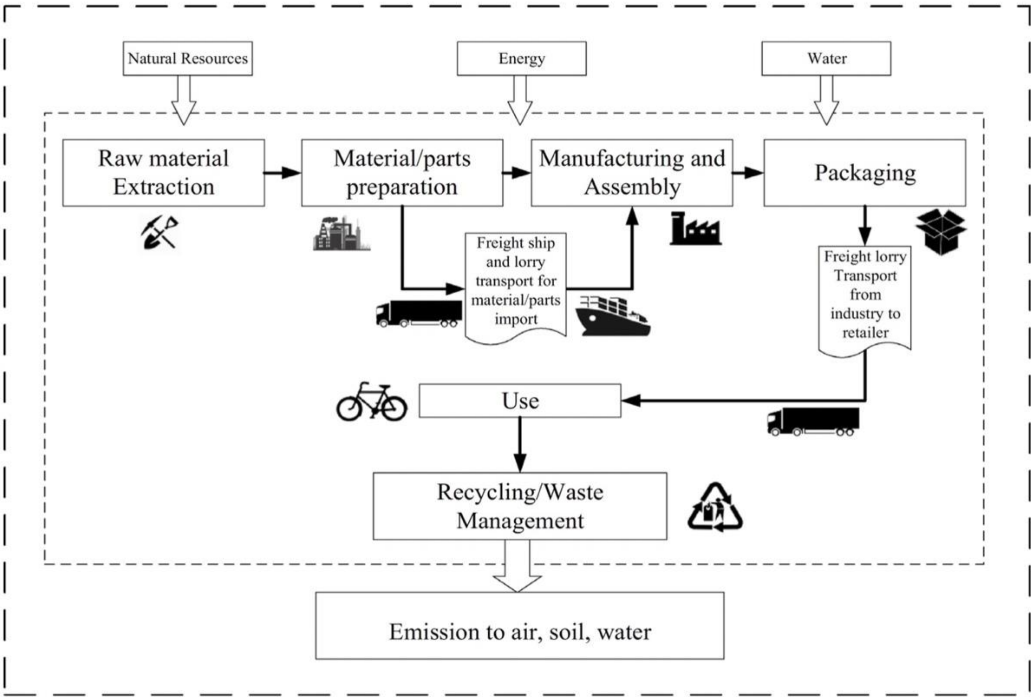

Figure 22: System boundary of LCA study of bicycle production in Bangladesh (Papon R, et al., 2019).

Table 6: LCI for bicycle production in Bangladesh(Papon R, et al., 2019).

Inputs	**value**	**unit**	**output**	**value**	**unit**
Aluminum alloyed	6.49	kg	Municipal solid waste	4.48	kg
Stainless steel	1.2	kg	Wastewater	7.1	m3
Steel alloyed	3.7	kg			
Wire	0.4	kg			
Plastic (Nylon)	1.5	kg			
PU, flexible foam	0.03	kg			
Rubber	1.4	kg			
Powder coat aluminum	0.21	kg			
Injection molding	0.98	kg			
Section bar extrusion, aluminum	2.5	kg			
Welding arc, aluminum	0.72	m			
Electricity	10.2	kWh			
Natural gas	0.325	m^3			
Tap water	0.71	kg			
Corrugated board	1.2	kg			
Packaging plastic	0.25	kg			
Packaging film	0.15	kg			

Table 7: Required components for maintaining a bicycle number of exchanges during its lifespan (Papon R, et al., 2019).

Component	**Number of exchanges**
Tire	4
Chain	1
Brake pads	6
Cassette	1

Measuring environmental impact via proposed framework as discussed above section and shown below:

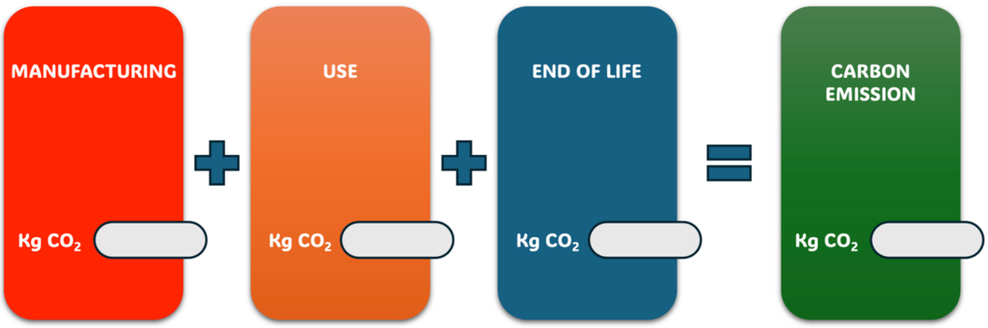

Figure 23: Proposed framework

Complete system life cycle analysis:

Step 1. Define lifetime, functional unit, and boundary

5 It is assumed that average lifespan of a bicycle is 15,000 km and tires need to be replaced in every 4000 km. Again, 1 chain, 6 brake pads (two wheels) and 1 cassette need to be replaced during the lifetime of a bicycle(Papon R, et al., 2019).

5 Average distance between industry and bicycle retailer shop of the domestic market was assumed as 100 km by heavy truck (16 ton). Moreover, impact of bicycle parts transportation from Japan, Taiwan and China was also accounted for. In this case, parts were transported from the correspondent country by sea (ocean freighter) to Bangladesh, and then, all these parts were carried in a heavy 16-ton truck up to industry, which was considered about 250-km travel distance(Papon R, et al., 2019).

After end use metals and plastic of bicycle are going to be controlled landfill.

Bicycle

Lifetime	15,000 km
Functional Unit	Impacts/life
System boundary	Excludes cleaning during use

Step 2. Make bill-of-materials

13

		value	unit	
Materials	Corrugated board	1.2	kg	
	Packaging plastic	0.25	kg	
	Packaging film	0.15	kg	
	Aluminum alloyed	6.49	kg	
	Stainless steel	1.2	kg	
	Steel alloyed	3.7	kg	
	S.Steel Wire	0.4	kg	
	Plastic	1.5	kg	
	PU, flexible foam	0.03	kg	
	Rubber	1.4	kg	
Manufacturing	Powder coat aluminum	0.21	kg	
	Injection molding	0.98	kg	
	Section bar extrusion, aluminum	2.5	kg	
	Welding arc, aluminum	0.72	m	
	Electricity usage	10.2	kWh	
	Natural Gas	0.325	m^3	
	Tap water	0.71	kg	
Use*	Tire (rubber + S.S wire)	0.44 (each)	kg	*: Replacement during use (4 tiers, 1 Chain, 6 brake pads and 1 cassette).
	Chain (S. Steel)	0.28	kg	
	Brakepad (rubber + Steel alloy)	0.29 (each)	kg	
	Cassette (steel alloyed)	0.34	kg	
Transport	Transportation by road	6440	kg.km	
Disposal	landfill			

Step 3. Calculate estimated impacts

Input	Amount	x CO_2 eq (kg)	= Value (kg)
Corrugated board	1.2 kg	0.44	0.53
Packaging plastic	0.25 kg	1.68	0.42
Packaging film	0.15 kg	1.22	0.18
Aluminium alloyed	6.49 kg	2.63	17.07
Stainless steel	1.2 kg	2.04	2.45
Steel alloyed	3.7 kg	0.907	3.36
S. Steel Wire	0.4 kg	2.04	0.82
Plastic	1.5 kg	4.218	6.33
PU, flexible foam	0.03 kg	4.8	0.14
Rubber	1.4 kg	1.77	2.48
Powder coat aluminum	0.21 kg	0.34	0.07
Injection molding	0.98 kg	0.59	0.58
Section bar extrusion, aluminum	2.5 kg	0.45	1.12
Welding arc, aluminum	0.72 kg	0.059	0.04
Electricity usage	10.2 kwh	1.18	12.04
Natural Gas	0.325 m^3	0.01	0.003
Tap water	0.71 kg	0.019	0.013
Transportation by road	644 kg.km	0.19	122.36
During Use			
Rubber	2.61 kg	1.77	4.62
S. Steel wire	1.6 kg	2.04	3.26
S. Steel	0.28 kg	2.04	0.57
Steel alloyed	1.38 kg	0.907	1.25
Controlled landfill			
Corrugated board	1.2 kg	0.54	0.65
Packaging plastic	0.25 kg	0.045	0.011
Packaging film	0.15 kg	0.05	0.007
Aluminum alloyed	6.49 kg	0.006	0.039
Stainless steel	1.48 kg	0.006	0.009
Steel alloyed	5.08 kg	0.006	0.03
S. Steel Wire	2 kg	0.006	0.012
Plastic	1.5 kg	0.29	0.43
PU, flexible foam	0.03 kg	0.04	0.0012
Rubber	4.01 kg	0.09	0.36

Total impact/life of bicycle: 181.26 kg CO_2 eq

The process is only accurate to 2 significant figures, so we calculate the impacts per functional unit and round to two significant figures:

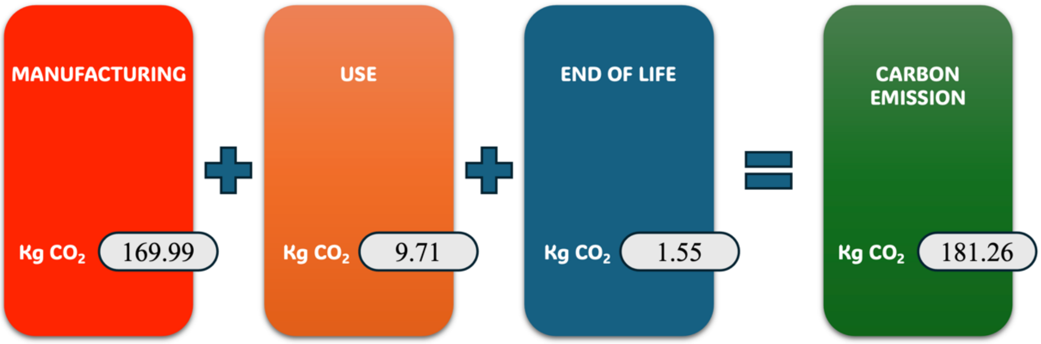

Figure 24: Environmental impact of bicycle at different stages

Results and discussion:

The traits of bicycles manufactured in Bangladesh are compiled in Table 8. The outcome was determined using the GPD framework, and it was then compared to the outcome of an article that had already been released which used the ReCiPe impact assessment technique to determine the outcome.

It is evident from the results that the manufacturing phase has the greatest environmental impact; energy consumption and the use of various metals, including aluminum, steel, and steel alloy, that are utilized in the production of pedal-cycles are proportionally high during this phase, resulting in a significant environmental impact. In contrast, as shown in Table 8, the use or maintenance phase has the second-highest environmental impact throughout the life cycle of pedal-cycle production in Bangladesh

Table 8: Environmental impact of bicycle at different stages for comparison with Papon Roy results.

Stages	***Kg CO_2 Eq***	***Kg CO_2 Eq* (Papon Roy)**
Manufacturing	168.86	174.08
Packaging	1.13	1.17
During use (for 15,000km life)	9.71	10
At the end of life	1.55	1.61
Total	181.26	186.86

To validate the proposed framework for green product design, the results obtained through its application were compared with those derived from established Life Cycle Assessment (LCA) software. The percentage error was calculated for key environmental parameters to assess the accuracy and reliability of the framework.

$$Percentage\ Error = \frac{|Measured\ Value - True\ Value|}{True\ Value} \times 100$$

The following table 9, summarizes the percentage error for each parameter, highlighting the deviations between the framework's results and the benchmark values. This analysis provides insights into the framework's performance and identifies areas for further refinement.

Table 9: A percentage error table.

Stages	**Measured Value (*Kg CO_2 Eq*)**	**True Value (*Kg CO_2 Eq*)**	**Percentage Error (%)**
Manufacturing	168.86	174.08	2.99

Packaging	1.13	1.17	3.42
During use (for 15,000km life)	9.71	10	2.90
At the end of life	1.55	1.61	3.73
Total	181.26	186.86	2.99

The results indicate that the proposed green product design framework demonstrates a high level of accuracy across all phases of the product lifecycle. The percentage error for individual phases—manufacturing (2.99%), packaging (3.42%), use (2.9%), and end-of-life (3.73%)—remains within an acceptable range, reflecting the reliability of the framework in estimating environmental impacts. The overall percentage error of 2.99% for the cumulative lifecycle assessment further validates the robustness of the framework. These results highlight the framework's potential as a practical tool for early-stage decision-making in sustainable product design, with minimal deviations from benchmark LCA software. Future refinements could focus on reducing the error in specific phases, such as the packaging and end-of-life phases, to further enhance its accuracy.

This research has some limitations that should be acknowledged. Furthermore, there was no direct access to manufacturers, and there was no knowledge about supply chain entities or transportation of components from suppliers to final assembly. This research can be improved by involving manufacturers. The study's findings can help with the design of sustainable consumer goods. It has been demonstrated that even motorcycles have environmental consequences. Careful material selection, optimal component design, and energy use can all contribute to a reduction in the life-cycle impacts of bicycle production.

This case study has been published in a Scopus-indexed journal, providing a detailed analysis of the bicycle's lifecycle and the potential for reducing its environmental impact through the application of the green product design framework. The publication can be referenced as follows:

Citation: Mohd Tayyab, Ranganath M Singari2,Peer M Sathikh, (2024), E Evaluating the Environmental Impact of a Bicycle: A Life Cycle Assessment with a New Green Product Design Framework., Educational Administration: Theory and Practice, 30(5), 3823-3831
Doi: 10.53555/kuey.v30i5.3539

7.4.2 Case Study 2: Evaluating the Environmental Impact of a Home Appliances

In this case study, ISO14040 was used to perform LCA of citrus juicer. This section discusses goal and scope, life-cycle inventory, and life-cycle effect assessment method which is a proposed novel GPD framework. The study's assumptions and sources of inventory data are also explained. According to the ISO standard, an LCA study consists of four steps: objective and scope definition, life-cycle inventory compilation, life-cycle assessment, and outcome interpretation. (ISO 2006).

A Life Cycle Assessment (LCA) study commences by establishing a well-defined scope, functional unit, and system boundaries. Subsequently, a comprehensive record of the resources and energy consumed at every phase of the product's life cycle is compiled. The inventory is subsequently utilized to conduct the impact assessment and calculate various environmental impacts, such as global warming potential.

In pursuance with the objectives of this research, the subsequent procedures were executed:

a. Information Collection From previous publication for life cycle inventory compilation given in Table 6.

b. Define and implement the Proposed GPD Framework for home appliance life cycle assessment.
c. Validation and Analysis of Data.

Information Collection From previous publication

- The functional unit for this study was extraction of a half-litre of juice per day. The life of each juicer was assumed to be 3 years (given three-year warranty by each manufacturer) (Shaukat et al., 2021).
- First juicer (J1) was produced in Slovenia and the second juicer (J2) was produced in China (Shaukat et al., 2021).
- It is postulated that the two juicers were conveyed from the port of Dammam to the retail establishment via vehicle after coming via sea. Both juicers are presumed to be disposed of via landfilling (Shaukat et al., 2021).
- Simapro software was used for modelling life-cycle inventory.

Figure 26, demonstrates the system boundary for the LCA study of both juicers, and Table 10 demonstrate the weight of various material used for both the juicers.

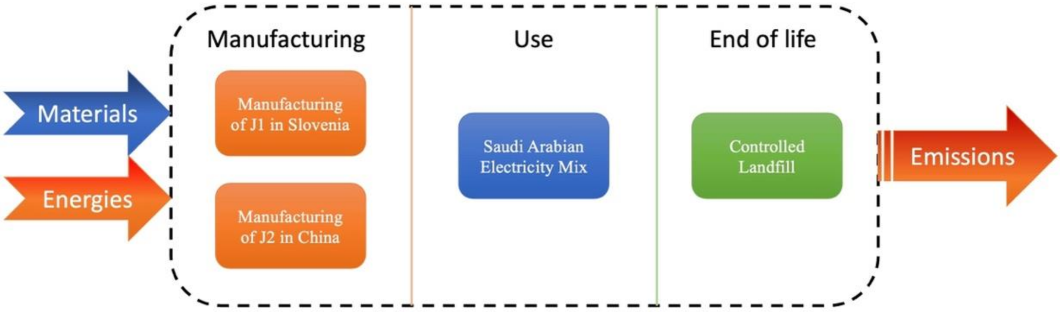

Figure 26: System boundary for both juicers.

Table 10: LCI for citrus juicer (Shaukat et al., 2021).

Material	**J1**	**J2**
Printed paper (g)	19	12
Cardboard for packaging(g) (corrugated board)	141	117
Polypropylene (g)	336	185
Polyethylene (g) (high density)	29	33
Polystyrene (g)	0	4
Styrene-acrylonitrile (g)	0	186
Steel unalloyed (g)	71	72
Permanent magnet (g)	19	15
Cast Iron (g)	2	2
Copper (g)	27	26
Chromium steel (g)	2	4
Cable (g)	76	114

Transportation, Energy consumption and manufacturing processes		
Transportation by road (kg.km)	18.175	19.275
Transportation by sea (t.km)	9.46	9.885
Electricity usage (MJ)	1.675	2.76
Steel processing (g) (sheet rolling)	69	70
Plastic bag production (g)	0	6
Polystyrene Foam production (g)	0	4
Injection molding of different plastic parts (g)	366	398
Copper wire drawing for motor (g)	26	24

Measuring environmental impact via proposed framework as discussed above section and shown below:

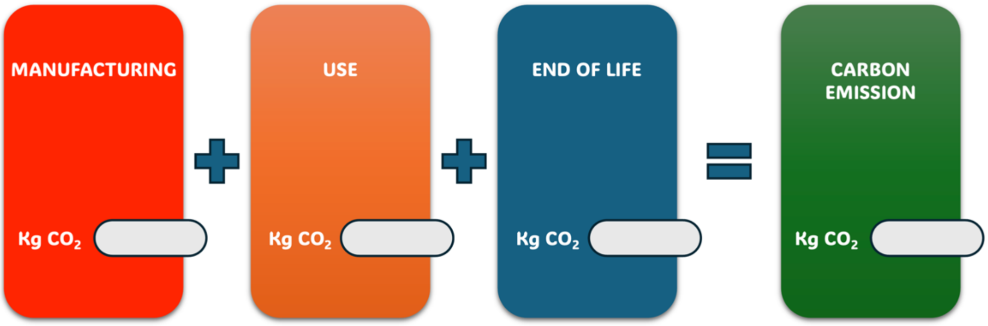

Figure 27: Proposed framework

Complete system life cycle analysis:

Step 1. Define lifetime, functional unit, and boundary

The functional unit for this study was extraction of a half-litre of juice per day. The life of each juicer was assumed to be 3 years (given three-year warranty by each manufacturer). Juicer J1 used an average of 7.5W and J2 used an average of 14W during juice extraction. Assumed controlled landfill at the end of the life cycle.

Juicer J1		**Juicer J2**	
Lifetime J1	24 x 365 x 3 = 26,280 hours	Lifetime J2	24 x 365 x 3 = 26,280 hours
Functional Unit	Impacts/life	Functional Unit	Impacts/ life
System boundary	Excludes cleaning during use	System boundary	Excludes cleaning during use

Step 2. Make bill-of-materials

	Juicer J1			**Juicer J2**	
Materials	Printed paper (g)	19	**Materials**	Printed paper (g)	12
	Cardboard for packaging(g)	141		Cardboard for packaging(g)	117

	(corrugated board)			(corrugated board)	
	Polypropylene (g)	336		Polypropylene (g)	185
	Polyethylene (g) (high density)	29		Polyethylene (g) (high density)	33
	Polystyrene (g)	0		Polystyrene (g)	4
	Styrene-acrylonitrile (g)	0		Styrene-acrylonitrile (g)	186
	Steel unalloyed (g)	71		Steel unalloyed (g)	72
	Permanent magnet (g)	19		Permanent magnet (g)	15
	Cast Iron (g)	2		Cast Iron (g)	2
	Copper (g)	27		Copper (g)	26
	Chromium steel (g)	2		Chromium steel (g)	4
Manufacturing	Steel processing (g) (sheet rolling)	69	**Manufacturing**	Steel processing (g) (sheet rolling)	70
	Plastic bag production (g)	0		Plastic bag production (g)	6
	Polystyrene Foam production (g)	0		Polystyrene Foam production (g)	4
	Injection molding of different plastic parts (g)	366		Injection molding of different plastic parts (g)	398
	Copper wire drawing for motor (g)	26		Copper wire drawing for motor (g)	24
Use	Electricity usage (MJ)	1.675	**Use**	Electricity usage (MJ)	2.76
Transport	Transportation by road (kg.km)	18.175	**Transport**	Transportation by road (kg.km)	19.275
	Transportation by sea (t.km)	9.46		Transportation by sea (t.km)	9.885
Disposal	landfill		**Disposal**	landfill	

Step 3. Calculate estimated impacts

Input	**Amount**	**x CO_2 eq** *(kg)*	**= Value** *(kg)*	**Input**	**Amount**	**x CO_2 eq** *(kg)*	**= Value** *(kg)*
Printed paper	0.019(kg)	0.68	0.01292	Printed paper	0.012(kg)	0.68	0.00816
Cardboard for packaging (corrugated board)	0.141(kg)	0.44	0.06204	Cardboard for packaging (corrugated board)	0.117(kg)	0.44	0.05148

Polypropylene	0.336(kg)	1.68	0.56448	Polypropylene	0.185(kg)	1.68	0.3108
Polyethylene (high density)	0.029(kg)	1.50	0.0435	Polyethylene (high density)	0.033(kg)	1.50	0.0495
Polystyrene	0	2.22	0	Polystyrene	0.004(kg)	2.22	0.00888
Styrene-acrylonitrile	0	1.86	0	Styrene-acrylonitrile	0.186(kg)	1.86	0.34596
Steel unalloyed	0.071(kg)	2.13	0.15123	Steel unalloyed	0.072(kg)	2.13	0.15336
Cast Iron	0.002(kg)	0.54	0.00108	Cast Iron	0.002(kg)	0.54	0.00108
Copper	0.027(kg)	1.86	0.05022	Copper	0.026(kg)	1.86	0.04836
Chromium steel	0.002(kg)	2.04	0.00408	Chromium steel	0.004(kg)	2.04	0.00816
Steel processing (sheet rolling)	0.069(kg)	0.16	0.01104	Steel processing (sheet rolling)	0.070(kg)	0.16	0.0112
Plastic bag production	0	0.25	0	Plastic bag production	0.006(kg)	0.25	0.0015
Polystyrene Foam production	0	1.18	0	Polystyrene Foam production	0.004(kg)	1.18	0.00472
Injection molding of different plastic parts	0.366(kg)	0.59	0.21594	Injection molding of different plastic parts	0.398(kg)	0.59	0.23482
Copper wire drawing for motor	0.026(kg)	0.21	0.00546	Copper wire drawing for motor	0.024(kg)	0.21	0.00504
Transportation by road	18.175 (kg.km)	0.27	4.90725	Transportation by road	19.275 (kg.km)	0.27	5.20425
Transportation by sea	9.46 (t.km)	0.027	0.25542	Transportation by sea	9.885 (t.km)	0.027	0.266895
During Use				**During Use**			
Electricity usage	1.675(MJ)	4.25	7.11875	Electricity usage	2.76(MJ)	4.25	11.73
Controlled landfill				**Controlled landfill**			
Printed paper	0.019(kg)	0.43	0.00817	Printed paper	0.012(kg)	0.43	0.00516
Cardboard for packaging (corrugated board)	0.141(kg)	0.54	0.07614	Cardboard for packaging (corrugated board)	0.117(kg)	0.54	0.06318
Polypropylene	0.336(kg)	0.045	0.01512	Polypropylene	0.185(kg)	0.045	0.008325
Polyethylene (high density)	0.029(kg)	0.049	0.001421	Polyethylene (high density)	0.033(kg)	0.049	0.001617
Polystyrene	0	0.054	0	Polystyrene	0.004(kg)	0.054	0.000216
Styrene-acrylonitrile	0	0.27	0	Styrene-acrylonitrile	0.186(kg)	0.27	0.05022
Steel unalloyed	0.071(kg)	0.006	0.000426	Steel unalloyed	0.072(kg)	0.006	0.000432
Cast Iron	0.002(kg)	0.006	0.000012	Cast Iron	0.002(kg)	0.006	0.000012
Copper	0.027(kg)	0.006	0.000162	Copper	0.026(kg)	0.006	0.000156
Chromium steel	0.002(kg)	0.006	0.000012	Chromium steel	0.004(kg)	0.006	0.000024
Total impact/life Juicer J1: 13.50kg CO_2 eq				**Total impact/life Juicer J2: 18.57kg CO_2 eq**			

The process is only accurate to 2 significant figures, so we calculate the impacts per functional unit and round to two significant figures:
*Due to unspecified cable and magnet are used the impact of cable and permanent magnet are not calculated.

Environmental impact of juicer J1 and Juicer J2 at different stages as shown below in figure 28 (a) and 28 (b) respectively:

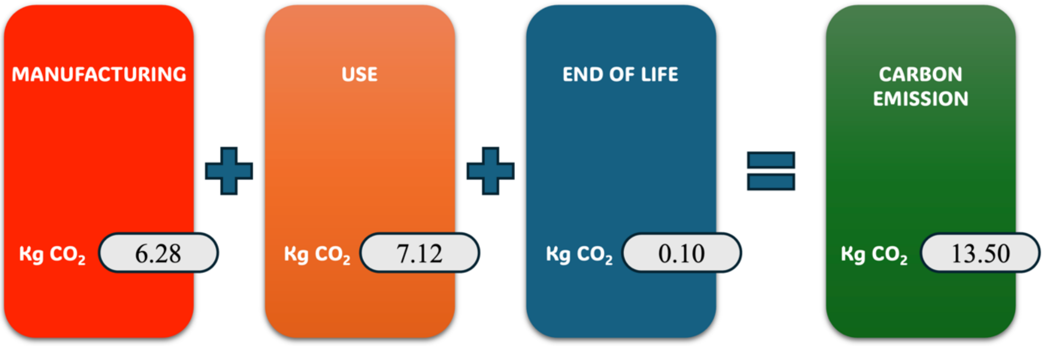

Figure 28 (a): Environmental impact of **juicer J1** during whole life cycle

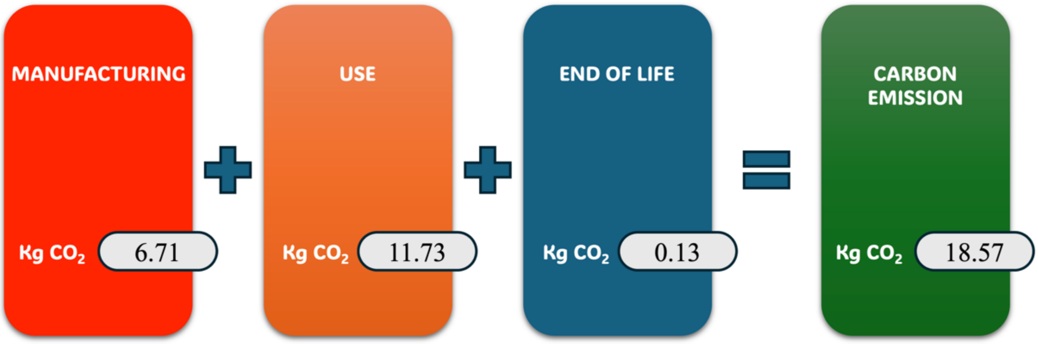

Figure 28 (b): Environmental impact of **juicer J2** during whole life cycle

Table 10 presents the characteristics of both juicers, also compared with published results. The outcome was determined utilizing the GPD framework and subsequently compared to the outcome of a previously published article that employed the ReCiPe impact assessment technique to ascertain the outcome.

As it is cleared from the result that the juicer J2 which is produced in China having higher environmental impact with compared to juicer J1 which is produced in Slovenia, and it is also cleared from the result that the use phase for both the juicers have majority of environmental impact. On the other hand, the manufacturing phase has second highest environmental impacts during the life cycle of both the juicers, as shown in table 11.

The study also discovered some interesting differences between the two juicers' motors. Compared to the motor used by J2, J1's motor is more effective and uses less power while in use, that's why during use phase juicer J1 impacts lesser than the juicer J2 environmentally.

Table 11: Environmental impact of both juicers J1 and J2 at different stages.

Stages	**J1** *(Kg CO_2 Eq)*	**J2** *(Kg CO_2 Eq)*	**J1(Published)** *(Kg CO_2 Eq)*	**J2(Published)** *(Kg CO_2 Eq)*
During manufacturing	6.28	6.71	6.10	6.5
During use (for 26,268hr life)	7.12	11.73	6.91	11.38
At the end of life	0.10	0.13	0.097	0.127
Total	13.50	18.57	13.10	18

To validate the proposed framework for green product design, the results obtained through its application were compared with those derived from established Life Cycle Assessment (LCA) software. The percentage error was calculated for key environmental parameters to assess the accuracy and reliability of the framework.

$$Percentage\ Error = \frac{|Measured\ Value - True\ Value|}{True\ Value} \times 100$$

The following table 12 summarizes the percentage error for each parameter of **Juicer J1** and table 13 summarizes the percentage error for each parameter of **Juicer J2**, highlighting the deviations between the framework's results and the benchmark values. This analysis provides insights into the framework's performance and identifies areas for further refinement.

Table 12: A percentage error table for **Juicer J1.**

Stages	**Measured Value** ***(Kg CO_2 Eq)***	**True Value** ***(Kg CO_2 Eq)***	**Percentage Error (%)**
Manufacturing	6.28	6.10	2.95
During use (for 26,268hr life)	7.12	6.91	3.04
At the end of life	0.10	0.097	3.09
Total	13.50	13.10	3.05

Table 13: A percentage error table for **Juicer J2.**

Stages	**Measured Value** ***(Kg CO_2 Eq)***	**True Value** ***(Kg CO_2 Eq)***	**Percentage Error (%)**
Manufacturing	6.71	6.5	3.23
During use (for 26,268hr life)	11.73	11.38	3.51
At the end of life	0.13	0.127	2.36
Total	18.57	18	3.17

The results indicate that the proposed green product design framework demonstrates a high level of accuracy across all phases of the product lifecycle. The percentage error for individual phases for juicer J1—manufacturing (2.95%), use (3.04%), and end-of-life (3.09%)—and for juicer J2—manufacturing (3.23%), use (3.51%), and end-of-life (2.36%)—remains within an acceptable range, reflecting the reliability of the framework in estimating environmental impacts. The overall percentage error for J1 and J2 of 2.99% and 3.17% respectively, for the cumulative lifecycle assessment further validates the robustness of the framework. These results highlight the framework's potential as a practical tool for early-stage decision-making in sustainable product design, with minimal deviations from benchmark LCA software. Future refinements could focus on reducing the error in specific phases, such as the packaging and end-of-life phases, to further enhance its accuracy.

The published research, which was carried out in Saudi Arabia, encountered obstacles including the scarcity of dependable local datasets, the absence of direct communication with manufacturers, and information regarding supply chain organizations and component transportation from suppliers to final assembly.

This case study has been published in a Scopus-indexed journal, providing a detailed analysis of the bicycle's lifecycle and the potential for reducing its environmental impact through the application of the green product design framework. The publication can be referenced as follows:

Citation: Mohd Tayyab, Ranganath M. Singari, and Peer M. Sathikh. "Evaluating the Environmental Impact of a Home Appliances: A Life Cycle Assessment with a New Green Product Design Framework." Educational Administration: Theory and Practice, SCOPUS/ESCI, Published,
DOI: 10.53555/kuey.v30i5.5674.

7.4.3 Validation Outcomes

The proposed framework for green product design was validated through two case studies: the environmental assessment of a bicycle and a home appliance (juicer). Both case studies aimed to assess the framework's accuracy in estimating environmental impacts by comparing its results with those obtained from established Life Cycle Assessment (LCA) software.

Case Study 1: Bicycle

For the bicycle, the percentage errors across the lifecycle phases were: manufacturing (2.99%), packaging (3.42%), use (2.9%), and end-of-life (3.73%). The cumulative lifecycle assessment showed an overall percentage error of 2.99%. These results indicate that the framework provides reliable estimates of environmental impacts, aligning closely with benchmark LCA tools.

Case Study 2: Juicer

For the juicer, the framework was tested on two models, **J1** and **J2**, to further validate its adaptability across different product designs:

- **Juicer J1**: Percentage errors for the manufacturing (2.95%), use (3.04%), and end-of-life (3.09%) phases were within acceptable limits. The cumulative lifecycle assessment showed an overall error of 2.99%.
- **Juicer J2**: The manufacturing, use, and end-of-life phases exhibited percentage errors of 3.23%, 3.51%, and 2.36%, respectively. The overall error for the lifecycle assessment was 3.17%.

These results confirm that the framework consistently provides accurate and reliable estimates for environmental impacts across different products. The minor deviations observed validate its robustness and practicality for lifecycle analysis. The consistency of results across the two case studies—bicycle and juicer—highlights the framework's adaptability and potential for application across diverse product categories. Its ability to achieve high accuracy with minimal computational effort underscores its suitability for integration into early-stage sustainable product design workflows.

CHAPTER 8:

RESULT AND DISCUSSION

8.1 RESULT:

The results from the systematic application of the Green Product Design (GPD) framework in two case studies—a bicycle and citrus juicers—provide comprehensive insights into the environmental impacts of products across their lifecycle phases. These case studies demonstrate the framework's ability to measure and mitigate carbon emissions at each phase, offering practical strategies for reducing environmental impacts in product design.

8.1.1 Case Study 1: Evaluating the Environmental Impact of a Bicycle

The proposed framework was applied to assess the environmental impact of a bicycle across its lifecycle phases: manufacturing, packaging, use, and end-of-life. The results were validated by comparing the framework's outcomes with those obtained from established Life Cycle Assessment (LCA) software.

The percentage errors for each lifecycle phase are summarized below:

- Manufacturing phase: **2.99%**
- Packaging phase: **3.42%**
- Use phase: **2.90%**
- End-of-life phase: **3.73%**
- Cumulative lifecycle assessment error: **2.99%**

These results indicate that the framework closely approximates the benchmark LCA tools, demonstrating its reliability and accuracy in estimating environmental impacts. The minimal deviations highlight the framework's ability to provide practical and efficient lifecycle assessments for green product design.

8.1.2 Case Study 2: Evaluating the Environmental Impact of Appliances (Citrus Juicers)

To test the adaptability of the framework, it was applied to two juicer models, **J1** and **J2**, to assess their environmental impacts across manufacturing, use, and end-of-life phases. The results and errors are summarized as follows:

- **Juicer J1**
    - Manufacturing phase: **2.95%**
    - Use phase: **3.04%**
    - End-of-life phase: **3.09%**
    - Cumulative lifecycle assessment error: **2.99%**
- **Juicer J2**
    - Manufacturing phase: **3.23%**
    - Use phase: **3.51%**
    - End-of-life phase: **2.36%**
    - Cumulative lifecycle assessment error: **3.17%**

The results for both models demonstrate the framework's accuracy, with percentage errors consistently within an acceptable range. The slightly higher errors observed for Juicer J2 indicate areas for potential refinement, particularly in the use phase.

8.2 DISCUSSION:

The results of the case studies provide clear evidence of the GPD framework’s ability to evaluate and improve the environmental performance of products across their entire lifecycle. Several key insights emerged from the results:

8.2.2 Lifecycle Focus on Energy and Material Efficiency

Across both case studies, the manufacturing and use phases were identified as the primary contributors to environmental impact. This reinforces the importance of focusing on energy and material efficiency in product design. In the bicycle case, reducing the environmental footprint of manufacturing processes—especially those involving energy-intensive materials like aluminium and steel—could lead to substantial emission reductions. Similarly, for household appliances like juicers, improving energy efficiency during use is critical, as this phase has the largest environmental impact.

The GPD framework encourages designers to prioritize energy-efficient designs, use of recycled materials, and streamlined manufacturing processes. The case studies show that even small changes in the choice of materials or motor efficiency can significantly reduce the overall environmental impact of a product.

8.2.3 Comparison with Conventional LCA Methods

The results from the GPD framework were consistent with those obtained from more complex LCA tools such as ReCiPe. This shows that the GPD framework is a reliable alternative for designers who may not have access to specialized LCA software. By simplifying the process into a single-figure scoring system, the GPD framework allows designers to quickly assess the environmental performance of different design alternatives. It serves as an effective tool for early-stage decision-making, enabling designers to iterate rapidly while keeping sustainability at the forefront.

8.2.4 Limitations and Areas for Improvement

While the GPD framework proved effective in identifying major environmental impacts, it has some limitations. The framework focuses primarily on carbon emissions and does not account for other environmental factors such as water usage, toxic emissions, or resource depletion. Future iterations of the framework could expand to include these dimensions, providing a more comprehensive assessment of environmental sustainability.

Additionally, the case studies revealed some limitations in data access, particularly regarding supply chain information. In both studies, data on the transportation of components and their suppliers were limited, which could affect the accuracy of the environmental assessments. Engaging directly with manufacturers and obtaining detailed supply chain data would improve the precision of future LCA studies using the GPD framework.

8.2.5 Practical Applications

The GPD framework’s accessibility and ease of use make it a valuable tool for industries aiming to adopt green product design practices. It provides actionable insights into how products can be designed to reduce their environmental footprint, from material selection to energy use and end-of-life disposal. The framework can be applied to a wide range of industries, including automotive, electronics, and consumer goods, where sustainability is becoming a key competitive differentiator.

8.3 CONCLUSION:

The application of the GPD framework in these two case studies demonstrated its effectiveness in assessing and reducing the environmental impact of products across their lifecycle. By focusing on the most impactful phases—manufacturing and use—the framework provides designers with clear guidance on how to improve product sustainability. The results align well with conventional LCA methods, validating the framework's robustness and practical utility.

The GPD framework represents a significant step forward in making lifecycle assessments more accessible to designers and industries alike, promoting a more sustainable approach to product development. Future research should continue to refine the framework, expanding its scope to include a broader range of environmental factors and ensuring its applicability across different product categories and industries.

CHAPTER 9:

CONCLUSION

This chapter concludes the research on developing a framework for Green Product Design (GPD), which focuses on integrating sustainability principles throughout the product lifecycle. The study addresses several key objectives, including the use of recycled and green materials, the analysis of flexibility, control, and sensitivity concerning green constraints, and the development of a practical method for efficient green product design. The findings of the research are summarized below, reflecting each research objective.

This study set out to develop and validate a **Green Product Design framework** aimed at integrating sustainability into the product development process. The framework was grounded in **Life Cycle Assessment (LCA)** methodologies and was designed to calculate the environmental impact, particularly **carbon emissions**, across different phases of the product lifecycle. The GPD framework was tested on two real-world case studies: a **bicycle** and **household appliances (citrus juicers)**. Key findings from this research are summarized below:

Manufacturing Phase Dominates Environmental Impact: In both case studies, it was observed that the **manufacturing phase** accounted for the largest proportion of environmental impact. This was primarily due to the energy-intensive processes involved and the choice of materials such as **aluminum, steel**, and **plastics**. In the case of the bicycle, the combination of material extraction and energy used during the **extrusion and injection molding** processes resulted in significant carbon emissions. Similarly, the use of plastics and metals in the manufacturing of juicers contributed to high emissions during this phase.

Use Phase Critical for Household Appliances: For energy-consuming products, such as the citrus juicers, the **use phase** emerged as particularly critical, accounting for a substantial portion of the product's environmental impact. The energy consumed during product usage, influenced by factors such as the efficiency of components like motors, played a key role in determining the overall carbon footprint. These findings emphasize the importance of designing energy-efficient appliances to mitigate the environmental impact over the product's lifetime.

Consistency with LCA Standards: The GPD framework, when compared to established LCA methodologies, demonstrated consistent results. This validation highlights that the GPD framework is both reliable and robust, offering a streamlined and accessible tool for designers and engineers without compromising the accuracy of environmental assessments.

End-of-Life Phase Impact: In both the bicycle and juicer case studies, the **end-of-life phase** was found to have the least impact on overall carbon emissions. This phase primarily involved the disposal or recycling of materials such as **steel, aluminum, rubber**, and **polypropylene**. While the impact was minimal compared to other lifecycle stages, it underscored the importance of end-of-life management, especially regarding material recovery and recycling.

9.1 SUMMARY OF FINDINGS:

1. **Use of Recycled and Green Materials**:

The study emphasized the significant environmental impact of material selection, particularly the use of energy-intensive materials like aluminum, steel, and plastics during the manufacturing phase. The framework demonstrated that opting for recycled and green materials could significantly reduce carbon emissions in both the bicycle and juicer case studies.

2. **Flexibility, Control, and Sensitivity in Early Product Lifecycle Stages**:

The Study highlighted the importance of addressing green constraints in the early design stages. Flexibility in material selection, control over manufacturing processes, and sensitivity to energy consumption during product use were critical to minimizing environmental impact. For instance, the juicer's energy-efficient motor was identified as a key factor in reducing its use-phase carbon footprint.

3. **Development of a Green Product Design Framework**:

The GPD framework successfully integrates LCA methodologies and proved consistent with established LCA tools. Validation through case studies demonstrated the framework's reliability and accuracy. For both the bicycle and juicer case studies, the percentage errors across lifecycle phases were consistently within an acceptable range (below 3.5%), with cumulative errors of 2.99% for the bicycle and 2.99%–3.17% for the juicer models. These results highlight the framework's ability to provide accurate environmental impact assessments, comparable to those of existing LCA software.

4. **Practical and Efficient Approach to Green Product Design**:

The research demonstrated that the GPD framework offers a practical and efficient approach to evaluating environmental impacts, particularly during the manufacturing and use phases. It simplifies the decision-making process for designers, enabling them to consider environmental performance early in the product lifecycle. This practical method ensures that sustainability is embedded in product design from the outset.

9.2 IMPLICATIONS FOR PRACTICE:

The development of the **Green Product Design framework** has practical implications for various industries, especially those involved in product development, manufacturing, and sustainability-focused operations. By providing a structured method for evaluating environmental impacts, the GPD framework can drive tangible changes in the way products are designed, manufactured, and managed. The implications for practice are detailed below:

1. **Informed Material Selection and Process Optimization**: The research findings highlight the substantial impact that material choices and manufacturing processes can have on a product's environmental footprint. By applying the GPD framework early in the design stage, product designers can make more **informed decisions** regarding the **selection of sustainable materials** and energy-efficient manufacturing processes. For instance, industries such as automotive, aerospace, and consumer goods could reduce carbon emissions by opting for **recycled materials**, adopting **lightweight composites**, and streamlining energy consumption during production.

2. **Energy Efficiency as a Design Priority**: For products that consume energy during their use phase (such as household appliances), the GPD framework underscores the importance of prioritizing **energy efficiency** in product design. This can be achieved through the integration of energy-saving components, better insulation, and the use of advanced technologies like **smart energy management systems**. In the case of consumer electronics, energy efficiency is becoming a significant selling point, and the GPD framework provides a roadmap for ensuring that products are designed to meet energy-efficiency standards.

3. **Simplification for Designers and Decision Makers**: The GPD framework simplifies complex LCA processes, allowing **designers and decision-makers** to quickly assess the environmental impact of their products without needing specialized LCA expertise. By integrating sustainability into the design process from the outset, companies can avoid the need for costly redesigns later on and meet growing regulatory and consumer demands for environmentally conscious products.

4. **Compliance with Global Sustainability Standards**: The GPD framework provides a tool for companies to align their product development processes with global sustainability standards, such as the **ISO 14040/44** LCA standards and the **European Union's Eco-design Directive**. By demonstrating a commitment to sustainable product design, companies can improve their corporate social responsibility (CSR) profile, attract eco-conscious consumers, and gain a competitive advantage in markets that increasingly prioritize environmental performance.

5. **Supporting Circular Economy Initiatives**: The GPD framework offers practical support for companies aiming to transition towards **circular economy models**, where products are designed for **reusability, recyclability**, and **remanufacturing**. By using the framework to assess end-of-life options and explore ways to extend product lifespans, companies can reduce waste and foster a more sustainable approach to production and consumption.

9.3 LIMITATIONS OF THE STUDY

While this research achieved significant progress in developing a practical framework for green product design, certain areas offer opportunities for enhancement and further exploration. These limitations reflect the natural scope of academic research and provide a foundation for future advancements:

1. **Focused Validation through Case Studies**: The framework was validated using two specific case studies—a bicycle and a household appliance—allowing for a detailed examination of its applicability in those contexts. While this targeted approach ensures depth, future studies can expand validation to diverse industries such as electronics, automotive, and consumer goods. Such expansion would showcase the framework's flexibility and universal applicability.

2. **Use of a Simplified LCA Methodology**: The adoption of a single-figure LCA methodology made the framework accessible and practical for practitioners. However, this simplification opens up avenues to integrate more nuanced, multi-metric LCA methods in future iterations, offering even deeper insights into environmental impacts without sacrificing usability.

3. **Reliance on OKALA Practitioner Guide Data**: Using OKALA data ensured consistency and reliability, but the scope of available attributes is currently tied to this source. Expanding the framework to include additional databases or region-specific carbon emission datasets would further enhance its relevance and adaptability to global contexts.

4. **Preliminary Technological Integration**: The study's methodology focused on practicality and manual processes, making it accessible to industries with varying technological capabilities. However, the opportunity exists to integrate cutting-edge technologies such as artificial intelligence or data visualization tools to automate certain aspects of the framework, increasing efficiency and scalability.

9.4 RECOMMENDATIONS FOR FUTURE RESEARCH

While the **Green Product Design framework** developed in this research has proven to be effective, there are several areas where further research is needed to enhance its scope and applicability. Future research directions include:

1. **Expanding Beyond Carbon Emissions**: The current framework primarily focuses on **carbon emissions** as the key indicator of environmental impact. Future research should aim to incorporate a wider range of environmental factors, such as **water usage**, **energy depletion**, and **chemical toxicity**, to provide a more comprehensive view of a product's overall environmental footprint. By doing so, the framework could offer a broader set of metrics for companies seeking to minimize their ecological impact.

14

2. **Integration with Circular Economy Principles**: Future research should explore how the GPD framework can be integrated with the principles of the **circular economy**, which emphasizes keeping products, components, and materials at their highest utility and value at all times. This could involve the development of new assessment methods that evaluate the potential for product **reuse, remanufacturing, and recycling**, thereby facilitating more sustainable product lifecycles.
3. **Customization for Industry-Specific Applications**: While the current framework has been tested on two case studies, future research could focus on customizing the GPD framework for specific industries with unique sustainability challenges, such as **automotive, textiles**, or **packaging**. By tailoring the framework to suit different industry needs, it can provide more targeted recommendations for reducing environmental impact.
4. **Exploration of New Technologies**: Emerging technologies, such as **additive manufacturing (3D printing)** and **digital twin simulations**, offer exciting opportunities to further reduce environmental impact during the manufacturing and design phases. Research could investigate how these technologies can be integrated into the GPD framework to optimize resource use and minimize waste.
5. **Collaboration with Industry for Data Sharing**: Access to accurate supply chain data remains a significant challenge in lifecycle assessment. Future research could focus on fostering **collaborations between academia and industry** to obtain more granular data on material sourcing, energy consumption, and logistics. Such collaborations would improve the accuracy and reliability of environmental impact assessments using the GPD framework.
6. **Development of Tools for Real-Time Assessment**: Future research should also consider developing **real-time assessment tools** that can provide continuous feedback during the design and development stages. These tools would allow designers to monitor the environmental impact of their choices dynamically, ensuring that sustainability considerations are embedded throughout the entire product development process.

Final Remarks

The proposed framework for green product design offers a practical, adaptable, and efficient solution for integrating environmental sustainability into product development processes. By enabling designers to assess environmental impacts early in the concept phase, the framework promotes informed decision-making that aligns with sustainability goals. With further refinement and broader validation, the framework has the potential to drive significant progress toward sustainable design practices across industries, contributing to global efforts to mitigate environmental challenges.

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List of Publications:

Journal Publication:

8) Mohd Tayyab, Ranganath M. Singari, and Peer M. Sathikh. "Evaluating the Environmental Impact of a Bicycle: A Life Cycle Assessment with a New Green Product Design Framework." Educational Administration: Theory and Practice, SCOPUS/ESCI, Published, DOI: 10.53555/kuey.v30i5.3539.

9) Mohd Tayyab, Ranganath M. Singari, and Peer M. Sathikh. "Evaluating the Environmental Impact of a Home Appliances: A Life Cycle Assessment with a New Green Product Design Framework." Educational Administration: Theory and Practice, SCOPUS/ESCI, Published, DOI: 10.53555/kuey.v30i5.5674.

10) Mohd Tayyab, Shadab Ahmad, Md Jamil Akhtar, Peer M. Sathikh, and Ranganath M. Singari. "Prediction of Mechanical Properties for Acrylonitrile-Butadiene-Styrene Parts Manufactured by Fused Deposition Modelling Using Artificial Neural Network and Genetic Algorithm." International Journal of Computer Integrated Manufacturing, SCI, Published, DOI: 10.1080/0951192X.2022.2104462.

Conference Presentations:

11) Mohd Tayyab, Ranganath M. Singari, and Peer M. Sathikh. "Understanding the Interplay of Flexibility, Control & Sensitivity Towards Green Constraints in Product Design: A Review." International Conference of Advance Research and Innovation (ICARI-2024), Organized by International Journal of Advance Research and Innovation (Google Scholar), 28th January 2024, Delhi State Centre, Institution of Engineers (Engineers Bhawan), New Delhi.

12) Mohd Tayyab, Ranganath M. Singari, and Peer M. Sathikh. "Design for Impact: A Framework for Green Product Design." International Conference of Advance Research and Innovation (ICARI-2024), Organized by International Journal of Advance Research and Innovation (Google Scholar), 28th January 2024, Delhi State Centre, Institution of Engineers (Engineers Bhawan), New Delhi.

13) Mohd Tayyab, Ranganath M. Singari, and Peer M. Sathikh. Study of Green Materials and Processes for Development of Green Product Design. International Conference of Design and Materials (ICDM-2023), Organized by NIT Delhi, July 2023, NIT Delhi, New Delhi.

14) Mohd Tayyab, Ranganath M. Singari, and Peer M. Sathikh. Comparative Analysis of Carbon Footprint and Environmental Impact of Laptops. International Conference of Design and Materials (ICDM-2023), Organized by NIT Delhi, July 2023, NIT Delhi, New Delhi.

About Mr. Mohd Tayyab:

Mohd Tayyab was born on September 1, 1988, in Aligarh, Uttar Pradesh, India. He completed his Bachelor of Technology (B.Tech) in Mechanical Engineering from the prestigious Zakir Husain College of Engineering and Technology (Z.H.C.E.T) at Aligarh Muslim University (AMU), one of India’s leading central universities. His academic journey took a significant step forward when he qualified for the Graduate Aptitude Test in Engineering (GATE) in 2016. This achievement paved the way for his admission to a master’s program in Production Engineering at Delhi Technological University (DTU), one of India's top-ranked institutions for engineering and technology.

From the very beginning, Mohd Tayyab exhibited a deep passion for creativity, innovation, and product design. His academic background, combined with a natural curiosity for cutting-edge technological advancements, fueled his desire to pursue further research in product design. He embraced the challenge of becoming a Ph.D. candidate in Design, qualifying for admission at DTU. During his time at the university, he not only focused on his research but also took on leadership roles in organizing various academic events. He played a key role in organizing four international conferences, two Faculty Development Programs (FDPs), and more than 12 expert lectures, showcasing his dedication to knowledge sharing and academic collaboration.

One of the most significant milestones in his academic journey came when he was invited to the School of Arts, Design, and Media at Nanyang Technological University (NTU), Singapore. From August 2022 to January 2023, he was able to advance his research in one of the world’s leading institutions for design and media. This opportunity was a dream come true for Tayyab, enabling him to work alongside global experts and further enhance his expertise in product design and innovation.

His dedication to research has resulted in the publication of over 10 research papers in reputed journals and conferences. A multilingual scholar, Mohd Tayyab is fluent in English, Hindi, and Urdu, which adds to his versatility as a global researcher and communicator.

Looking forward, Tayyab remains committed to pushing the boundaries of product design research. He is particularly keen to continue his research collaborations with NTU, Singapore, aiming to contribute further to the fields of design and innovation on a global scale.