A FRAMEWORK FOR FRUGAL DESIGN AND ITS ASSESSMENT

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

DOCTOR OF PHILOSOPHY

by

Anuradha Kumari
(2K19/PHDDES/02)

Under the Supervision of

Dr. Ravindra Singh
Assistant Professor, Department of Design
Delhi Technological University

Prof. Lalit Kumar Das
Hon. Dis. Faculty, Department of Design
Delhi Technological University

Department of Design

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Shahbad Daulatpur, Main Bawana Road, Delhi-110042. India

December, 2025

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to the many people who contributed to this research.

First and foremost, I am profoundly indebted to my supervisors, Dr. Ravindra Singh and Prof. Lalit Kumar Das, for their invaluable guidance, patience, and inspiration at every research stage. Their expertise, unwavering support, and constant motivation were instrumental in shaping this work. It has been an immense privilege and honor to work under their mentorship.

My heartfelt thanks go to my beloved husband and son, whose unconditional love, understanding, and sacrifices allowed me to dedicate myself fully to this pursuit. My husband's unwavering support in managing household responsibilities and his encouragement during challenging times were my pillars of strength.

I am deeply grateful to my parents for their lifelong encouragement, prayers, and belief in my abilities. Their moral support has been a constant motivation throughout my academic journey.

I sincerely appreciate the insightful feedback and suggestions from Prof. Anil Gupta, Prof. Jaideep Prabhu, Dr. Ajay Thakur, Prof. Ranganath M. Singari, Prof. Roli Purwar, and Prof. R.C. Singh during seminars, discussions, and reviews of my work. Their constructive criticism greatly enriched this research.

I am also thankful to my dear friends for their emotional support and laughter, which kept me grounded.

Lastly, I acknowledge all those who contributed indirectly- teachers, mentors, and well-wishers, whose influence has shaped my academic and personal growth.

Anuradha Kumari

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Shahbad Daulatpur, Main Bawana Road, Delhi-42

CANDIDATE'S DECLARATION

I, **Anuradha Kumari,** hereby certify that the work which is being presented in the thesis entitled "**A Framework for Frugal Design and Its Assessment**" 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 from August, 2019 to August, 2025 under the supervision of **Dr. Ravindra Singh** & **Prof. Lalit Kumar Das.**

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other Institute.

Candidate's Signature

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Shahbad Daulatpur, Main Bawana Road, Delhi-42

CERTIFICATE BY THE SUPERVISOR(s)

Certified that **Anuradha Kumari (**2K19/PHDDES/02) has carried out their search work presented in this thesis entitled **"A Framework for Frugal Design and Its Assessment"** for the award of **Doctor of Philosophy** from the Department of Design, Delhi Technological University, Delhi, under our supervision. The thesis embodies the results of original work, and the student herself carries out studies. The contents of the thesis do not form the basis for the award of any other degree to the candidate or anybody else from this or any other University/Institution.

Signature
Dr. Ravindra Singh
Assistant Professor
Department of Design
Delhi Technological University

Signature
Prof. Lalit Kumar Das
Distinguished Faculty
Department of Design
Delhi Technological University

Date:

ABSTRACT

The global challenges of environmental degradation and unequal access to the benefits of technological developments require a significant shift in how we approach product design and development. Traditional resource-intensive design practices are not sustainable, and current innovations often fail to achieve a critical portion of the world's population due to cost and adaptability issues. This research addresses these challenges by developing a Design framework as a generally applicable strategy for creating effective and sustainable solutions.

In this research, we have developed a design framework that is frugal in terms of resource consumption throughout its lifecycle. The frugal design framework consists of five dimensions, beginning with redefining the frugal design concept. Moving beyond the commonly held perception of frugal design as an affordable innovation for marginalized communities, this research proposed a new universal understanding of the frugal design concept. Frugal design (FD) is defined as a resource-conscious innovation that develops high-performance, long-term, sustainable functional solutions. This expanded perspective goes beyond specific economic or geographical boundaries. Frugal design is seen as a globally relevant, strategically advantageous approach to various design challenges in various industries and contexts. This reconceptualization forms the basis for identifying essential attributes that define effective frugal design: sustainability, function, inclusion, and performance. These attributes are interconnected dependencies that must be harmoniously integrated throughout the design and development process. These attributes emphasize creating products that minimize resource consumption and environmental impact over the lifecycle, providing essential and reliable functionality, and are accessible, relevant, or exceed required performance standards in the intended operational context of a diverse global user base. Later, this research introduces a frugal design evaluation model (FDEM) for practicing these attributes. This evaluation model is developed through identified core attributes and enhanced with user feedback. Frugality index, defined on a scale of 1-5, measures the product's frugality quotient based on associated criteria/attributes. It also guides the designers to improve designs based on user insights, indicating the criteria the product lacks and making them understand why some products and features are acceptable over others at the user level. Furthermore, to understand the systemic challenges hindering the broader adoption of FD, the research delves into a comprehensive analysis of the entire product lifecycle, revealing the inefficient and wasteful use of key input resources (material, energy, information, time, and space) are major and frequently disregarded contributing factor to the inability to get frugal design outcomes.

A central contribution to this research is developing an IO(Input-output) frugal design framework. A structured and systematic approach is presented to optimize resource use for various design processes. The main goal of this framework is to streamline the development process by strategically focusing on critical input resources (e.g., materials, energy, information, space, time, etc.), the generation of valuable outputs (e.g., sustainability, function, inclusion, performance improvements, etc.), and simplifying inherently complex systems and strategically effective values. This IO framework provides designers and decision makers with a more informed strategic foundation for resource allocation and design compromises, enabling them to

create sustainable and integrated solutions by optimizing critical resources. Quantifying the complex relationship between specific design decisions and their concrete effects on frugal design outcomes. This innovative approach substantially advances traditional, often more intuitive, experience-based design processes.

Overemphasizing frugality with respect to five input resources can result in solutions that, while meeting resource efficiency goals, compromise user experience, which prevents widespread adoption and eventually minimizes the intended benefits of frugal design. Therefore, including Design Thinking (DT) in the frugal design paradigm provides a promising path to expand its capabilities.

This research develops a frugal design thinking (FDT) framework. Recognizing the inherent limitations of traditional linear and often closely focused problem-solving methods, especially when facing the complexity and dynamic limitations of resource-scarce environments. FDT offers a powerful synergistic integration of the core principles and iterative processes of Design Thinking (DT) and the resourcefulness and value-orientation of Frugal Design (FD). This integrated approach provides a structured yet highly adaptive, human-centric methodology for manufacturers to effectively address multifaceted manufacturing and design challenges in a resource-limited context. This new framework represents a key contribution to the field with a practical and implementable roadmap to promote the ubiquitous culture of economic innovation within an organization, while simultaneously promoting the creation of effective solutions that effectively meet global needs related to sustainability, accessibility, and affordability. The FDT framework provides a transformative perspective on how design is used in an increasingly resource-conscious, interconnected world, providing both practitioners and researchers with the tools to advance frugal design principles and practices for a more sustainable and equitable future.

List of Publications

Published Papers
Journal:

1. Kumari, A., Singh, R., and Das, L. K. "A Conceptual Model to Assess the Effectiveness of Frugal Product Design Frameworks*, IEEE Transactions on Engineering Management*.

2. Kumari, A., Singh, R., and Das, L. K. (2025). Uncovering The Barriers: The Root Causes Of Frugal Design Failure. *International Journal of Environmental Sciences*, *11*(11s), 1061–1076.

Conference:

1. Kumari, A., Singh, R., and Das, L. K. (2023, December). Frugal Design: An Empirical Conceptualization and Measurement. In *2023 International Conference on Sustainable Technology and Engineering (i-COSTE)* (pp. 1–6). IEEE.

2. Kumari, A., Singh, R., and Das, L. K. (2025). "An approach to evaluate the Accessibility and inclusion of public space," *in Artificial Intelligence in Computational Material Science: Methods and Applications*

Communicated/under review Papers:

1. Kumari, A., Singh, R., & Das, L. K. "An Approach to Developing a Frugal Design Thinking Framework," Journal of Mechanical Design.
2. Kumari, A., Singh, R., & Das, L. K. "The Frugal Innovation Pyramid: A Taxonomy of Innovation Phenomena in the Frugal Product Design Field," Journal of Advanced Design.
3. Kumari, A., Singh, R., & Das, L. K. "Redefining Frugal Innovation: Insights from Semantics and Pragmatic Perspective," Technovation.
4. Kumari, A., Singh, R., & Das, L. K. "Fostering Frugal innovation: A stakeholder-centered design thinking framework," Discover Sustainability.
5. Kumari, A., Singh, R., & Das, L. K. "An Input-Output Model for Frugal Design: A Framework for Resource-Conscious Innovation" IEEE Transactions on Engineering Management.

Table of Contents

List of Figures

List of Tables

Abbreviation

Frugal Design	FD
United Nations Organization	UNO
Frugal Design Evaluation Model	FDEM
Input-Output Analysis	IO-S
Frugal design thinking	FDT
Design Thinking	DT
U.S. Public Interest Research Group	US PIRG
UN Environment Programme	UNEP
Principal Component Analysis	PCA
Item-Content Validity Index	I-CVI
Content Validity Ratio	CVR
Bottom of the pyramid	BOP
Frugal Design Evaluation Model	FDEM
Root cause analysis	RCA
Analytical Hierarchy Process	AHP
Canonical Correlation Analysis	CCA

Chapter 1

INTRODUCTION

"The World has enough for everyone's needs, but not enough for everyone's greed"- Mahatma Gandhi.

According to the United Nations Organization (UNO), there are approximately 8 billion people on the planet, of which 647 million people in emerging nations are exposed to acute poverty and struggle for livelihood. This population will rise to 9.7 billion by 2050 (United Nations, 2025). This extremely rapid population growth will undoubtedly lead to many problems, such as difficulty meeting the population's basic needs and maintaining a good quality of life. As resource demand continues to rise for goods and services, so will resource consumption, and the absence of responsible waste management and awareness results in environmental challenges, i.e., biodiversity loss and climate change. Integrating Frugal Design (FD) into current product design practices is essential to reduce resource depletion while meeting the population's needs.

1.1 Selection of Subject and Problem Background

In a world where resources are scarce, technology commercialization has become a double-edged sword. Although it incites innovation, the consumption-driven economy constantly forces businesses to produce products with limited lifespans (Binswanger, 2001). A perpetual cycle of "new is better" has fuelled an endless vortex of waste, accelerated the depletion of resources, and strained the environment (Powell, 2022). This strategy restricts inclusive and sustainable growth and challenges efforts to conserve resources. The problem is apparent: Could technological developments be used to create innovative products with optimum resource utilization and less waste?

Therefore, organizations must prioritize the development of long-lasting products and services that deliver "more value, with fewer resources" for both users and enterprises (Le Bas, 2016; Leliveld and Knorringa, 2018). Product development is a crucial driver of economic growth as it creates innovative solutions that improve individual well-being while enabling businesses to sustainably (Oosterwal, 2010). Furthermore, innovation is becoming an increasingly important aspect of development. Also, constantly shifting customer requirements and preferences have turned the focus of traditional enterprises toward customers, who demand more value in products and services along with affordable prices (Labrecque et al., 2013). Traditional product design approaches have failed to meet market demands, thus shifting the focus to a resource-constrained product design approach.

In the 2010s, innovation analysis underwent a fundamental change with the introduction of "frugal design." Products were developed using a "frugality lens," emphasizing resourcefulness and cost-effectiveness. The research on frugal design begins within the context of developing markets. The primary goal is to create products and services that meet the needs of these markets, are cost-effective, and provide end consumers with sufficient value (Prahalad and Hart, 2002; Soni and Krishnan, 2014). To achieve this while considering diverse user needs, products should be resource-efficient and deliver core functionality at an affordable cost.

Current research does not provide a global understanding of frugal design since it is often limited to low-income consumers or developing economies. This restricted perspective makes it more challenging to comprehend how cost-consciousness and resourcefulness may spur innovation in every context (Sarker, 2022). A consensus on the frugal design concept is crucial for a more inclusive and holistic approach to innovation. Despite the recognized importance of Frugal Design (FD), research is insufficient for optimizing frugality throughout a product's lifecycle. The importance of frugal design has been well documented, yet the lack of quantitative metrics impedes a comprehensive evaluation of the concept (Webb et al., 2021). The thesis is driven by the desire to provide a framework for frugal design that can be globally accepted in innovation while addressing the requirements of sustainability and inclusion.

1.2 Motivation for this research

Understanding and practicing the design processes made it realize that any product or service should be inclusive, sustainable, and resourceful. This principle has led the researchers to a frugal design approach that embodies these values by highlighting “ingenuity over surplus.” The researcher is motivated to examine how constraints can inspire innovation and ensure functionality and accessibility without compromising quality or aesthetics. Frugal Design challenges us to rethink waste, prioritize real users' needs, and create solutions that serve different communities, especially those overlooked by traditional design. In addition to practicality, it is a responsible way of combining creativity and effectiveness, proving that thoughtful and minimal design is equitable and transformative. This philosophy inspires the researcher by ensuring that everyone can access meaningful solutions. The motivations for this research are as follows:

- Traditional design approaches continue to exacerbate environmental degradation through resource-intensive production. This key challenge motivates the researcher to develop a frugal design framework.
- Despite ongoing advancement in design innovation, affordability and adaptation restrictions exclude almost 40% of the world's population (World Bank, 2023). This sustained inequality is a key issue and core motivation of this research.
- The fundamental challenge is achieving sustainable development and economic strengthening worldwide through innovation that can be easily adapted to different economic and cultural contexts. Current innovation models often lack this critical adaptability, impeding effectiveness in various environments.
- Theoretical debates about frugal design are abundant but lack the robust, practical framework guidelines that designers and innovators can utilize.

1.3 Problem Formulation

Despite technological advances, the traditional product design process fails to meet the global population's needs due to its excessive reliance on increasingly scarce resources. The limitation of resources represents a significant entire life cycle. These design processes are not only unsustainable but also reinforce social exclusion. The high costs associated with resource-intensive production result in products beyond marginalized communities' financial reach.

As depicted in Fig. 1.1, the dominant generative model elucidates how sub-optimal utilization of resources triggers a series of challenges within our communities.

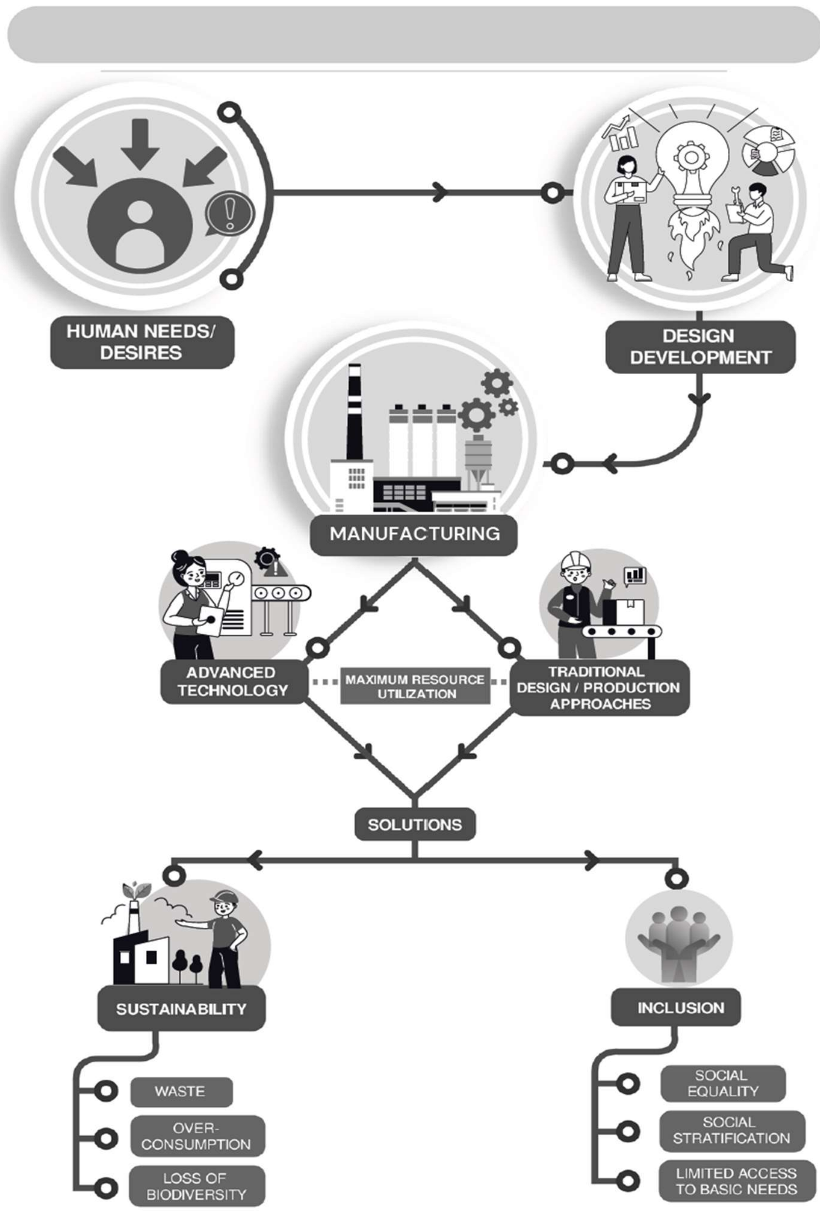


Fig. 1.1 Visualizing the Research Problem.

1.4 Research Aim and Objective

This research aims to develop a frugal design framework that prioritizes the efficient use of resources to develop user-centric solutions. The following objectives are to achieve this aim.

- To Redefine Frugal Design: Develop standardized, generally applicable definitions of frugal design that prioritize sustainability and social and economic inclusion beyond regional or context-specific interpretations.
- To identify the attributes of frugal design: Determine frugal design's measurable attributes, allowing quantification and assessment of frugal design's effectiveness.
- To develop a Frugal Design Evaluation Model (FDEM): Develop a structured evaluation model to quantify the product's efficiency and systematically measure the degree to which the existing products align with frugal design criteria.
- To investigate the root causes of product inefficiency throughout the lifecycle: Analyze the product lifecycle and identify factors hindering compliance with frugal design and production criteria. This leads to inefficiency and unsustainable outcomes.
- To develop and validate the frugal design framework: Develop an input-output (IO) frugal design framework that optimizes resource utilization in the design processes to enhance sustainability, performance, function, and inclusion of the design solutions.

1.5 Scope of the Research

The development of an inclusive and sustainable framework for frugal design is the primary goal of this research. It accomplishes this by taking inspiration from the practical and flexible solutions in nature. The scope covers the following areas:

- Identify Frugal Design Attributes: The research delves into the essential attributes that make frugal design practices successful. This entails reviewing prior literature and interacting with experts.
- Users' Perspectives: The research investigates the opinions of various users on the idea of frugality and how it is applied to design. This helps to make it easier to determine how to create frugal design solutions that satisfy the demands of all users.
- Develop a frugal design evaluation model (FDEM): A method to evaluate the degree of frugality attained in a design solution; designers can use this model to assess their products and pinpoint areas that need improvement.
- An Input-Output frugal design framework: The research has developed an input-output (IO) frugal design framework, a structured approach to optimizing resource utilization in a variety of design processes, particularly for resource-related or sustainable dedicated projects. The aim is to optimize development by focusing on critical inputs, maximizing valuable outputs, simplifying complex systems, and enabling effective value-added technologies.
- Foster inclusivity under resource scarcity: The research examines user preferences and behavior patterns in environments with limited resources. This allows us to better understand how to create resource-efficient, inclusive solutions that meet the needs of a wide range of users.

1.6 Research Plan

A detailed research plan was developed to answer the research gaps and define specific studies to accomplish that goal. Fig. 1.2 presents an overview of the research plan and includes a brief rationale for each investigation.

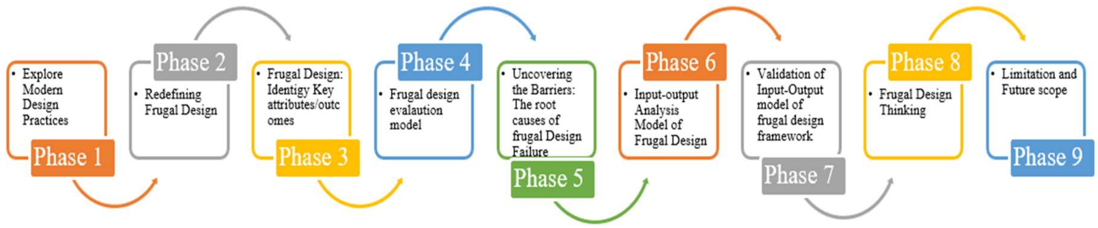


Fig. 1.2. Research Plan

This first phase of this research is the basis for developing a framework for frugal design. Researchers will examine modern design practices in this section, paying particular attention to strategies that put social inclusion, affordability, and sustainability at the forefront. Furthermore, this phase will entail precisely identifying the specific problem the research seeks to solve. In the following phases, this phase lays the foundations for creating a design framework that focuses on sustainability and inclusion. Phase 2 delves further into redefining frugal design by proposing a broader, integrated conceptualization beyond traditional connections with emerging markets. Frugal design should be recognized as a universal approach focusing on resource efficiency, simplicity, and sustainability that can be used in various economic and geographical contexts. Phase 3 entails identifying and elucidating the essential attributes that constitute frugal design. This phase comprehensively analyzes existing frugal design practices, methodologies, and principles across various contexts. Phase 4 of the research proposes a conceptual assessment model to assess the efficacy of frugal product design. The model is used to analyze the frugality of the design, and the current non-frugal products can be improved by incorporating the criteria that the designer neglected. Phase 5, performs a comprehensive product lifecycle analysis to uncover the underlying causes of frugal design failure. Using a closed-loop frugal product lifecycle modeling framework and several root cause analysis techniques, Phase 6, developed an Input-Output Analysis (IO-A) model for frugal design, aimed at systematically analyzing the correlation between design inputs (material, energy, Information, space, and time) and outputs (sustainability, inclusion, function, and performance). Phase 7, validating input-output models of frugal designs by examining five case studies. Phase 8, a framework for frugal design thinking (FDT). This novel method tackles manufacturing difficulties in resource-related contexts by combining design thinking (DT) and frugal innovation (FI). Finally, phase 9 entails the future scope and limitations of the research.

1.7 Thesis Structure and Flow

This thesis is divided into ten chapters, each with its unique content. The following is a quick outline of the topics covered in each chapter.

Chapter 1: The first chapter of this thesis introduces the primary problem while explaining the research endeavor's context and rationale. This section also briefly reviews standard design methods and their accompanying issues. Furthermore, the chapter defines the scope and objectives of the research, providing a framework for the following discussions and analyses.

Chapter 2: This chapter includes a detailed literature analysis on sustainability and inclusive design, particularly on frugal design. It investigates the current status of research in these disciplines, focusing on approaches for frugal product design. The review critically assesses existing design approaches, models, and tools, emphasizing their limitations and flaws. This analysis identifies the gaps in the research, necessitating a re-evaluation of the issue statement presented in this paper.

Chapter 3: This chapter redefined frugal design by proposing a broader, integrated conceptualization beyond traditional connections with emerging markets. The authors argue that frugal design should be recognized as a universal approach focusing on resource efficiency, simplicity, and sustainability that can be used in various economic and geographical contexts. By expanding its definition, this chapter aims to improve concepts' global relevance and adaptability to promote interdisciplinary innovation and sustainable development.

Chapter 4: This chapter identifies essential attributes of frugal design with the help of Principal Component Analysis (PCA), Content Validity Analysis, and Word Frequency Count. This chapter presents the framework developed as part of the work, where four critical attributes of frugal design, i.e., sustainability functionality, inclusion, and performance, are identified. The framework also underlines the importance of making the products more frugal for a wider society, including developed and developing countries, and all socioeconomic classes.

Chapter 5: This chapter proposes a conceptual assessment model to assess the efficacy of frugal product design. The model is based on existing literature on frugal design and identifies the key criteria for being frugal in the last chapter (i.e., Sustainability, Functional, Inclusion, and Performance). Further, the user experience of (n=150 users) was also incorporated into the model to provide valuable and relevant insight. The proposed model is used to analyze the frugality of the design, and the current non-frugal products can be improved by incorporating the criteria the designer neglected.

Chapter 6: This chapter performs a comprehensive product lifecycle analysis to uncover the underlying causes of frugal design failure. Using a closed-loop frugal product lifecycle modeling framework and several root cause analysis techniques, this research finds the inefficient use of essential input resources (materials, energy, information, space, and time) as a critical cause of failure.

Chapter 7: This chapter presents a novel adaptation of Input-Output Analysis (IO-A) for application in the frugal design domain, aimed at systematically analyzing the correlation between design inputs (material, energy, Information, space, and time) and outputs (sustainability, inclusion, function, and performance). Canonical Correlation

Analysis (CCA) examines the complex relationship between the input and output. It can usually reveal wise correlations and compromises beyond the scope of qualitative analysis. Providing a data-controlled approach opens the door to a frugal design concept that enables optimum resource use for creating sustainable integrated solutions.

Chapter 8: This chapter presents a methodological approach to validate input-output models of frugal designs by examining five case studies. This research initially records interdependencies between input variables (material, energy, information, space, and time), followed by an analysis of the impact on frugality knowledge, such as sustainability, function, and inclusion. Quantitative verification methods are used to determine the strength and consistency of these relationships. The results provide insight into factors that influence the development of Frugal products and provide a framework for companies that aim to improve the efficiency of their design processes.

Chapter 9: This chapter presents a frugal design thinking (FDT) framework. This new approach integrates design thinking (DT) and frugal design (FD) to address manufacturing challenges in resource-limited environments. Conventional problem-solving techniques frequently fall short in dynamic settings where resources are limited and must be meticulously managed. Frugal Design Thinking (FDT) facilitates the development of cost-effective, sustainable, and user-centric solutions while preserving essential functionalities.

Chapter 10: This chapter summarizes the completed research work and ends with a discussion of the work's contributions, future scope, and limitations.

Chapter 2

LITERATURE REVIEW

"A Literature review is a journey through the landscape of existing knowledge, with each source providing a new perspective or insight"- Elizabeth Kostova.

This chapter establishes the foundation for the research by investigating the key issues that point out the necessity for the development of a new design approach. It explores the evolving nature of design and addresses the challenges associated with traditional design and development processes, particularly incorporating sustainability and inclusion. It explores the concept of frugality by examining how nature serves as a perfect example of frugal practices and investigates existing frugal design frameworks that support its implementation. Finally, the chapter highlights the significant insights and outlines the research gaps, thereby establishing a clear path for current research and its contribution to the field of design.

2.1 Evolution of the Design and Its Influence on Society

Design changes from the service of elites to empowering the masses, reflecting changes in social values. What began as decorative craftsmanship transformed into functional solutions through industrialization and has transformed into sustainable and integrated practices. This explains the growing role of design in addressing global challenges, from the scarcity of resources to social inequality. The following sections outline this progression and its social impact.

2.1.1 Evolution of Design

The evolution of design can be understood through distinct phases- Design 1.0, 2.0, and 3.0- each representing a shift in approach, purpose, and complexity. Design 1.0 was explained as a plan, a series of steps that lead to a desired outcome (Corte-Real, 2010).

Design 2.0 refers to the cognitive process wherein a designer actor systematically develops products, processes, or systems. It consists of formulating a proposition or idea that guides and directs the design decision for a specific project (Design Council).

Design 3.0 extended beyond aesthetics; it also involves functionality, achieving goals, and adhering to limitations while also considering economic, environmental, and socio-political factors (Archer,1979).

The design has persistently evolved throughout history, adjusting to technological advancements, organizational structure changes, and cultural dynamics shifts while preserving its fundamental ability to cater to human needs (Steadman, 2008). Design 4.0 is now seen as a strategic tool emphasizing inclusivity (Jehlen, 2002), multidisciplinary collaboration, user-centered Design (Mao et al., 2005), and cultural diversity (Khalid, 2006). Design has shifted its emphasis to developing experimental aesthetics, embracing technological advancements (Poon, 2017), and generating meaningful experiences in the twenty-first century. This ongoing evolution signifies a dynamic domain that adapts to society's demands and anticipations, aiming to cultivate innovation, customer fidelity, and a competitive edge in an interconnected global community (Broadbent, 2002). The connection between design and society emphasizes the mutual dependence on technological advancements, human creativity, and social dynamics, which influence our interactions with tangible goods, services, and the physical environment (Whiteley, 1993). the phases of design evolution (see Fig. 2.1).

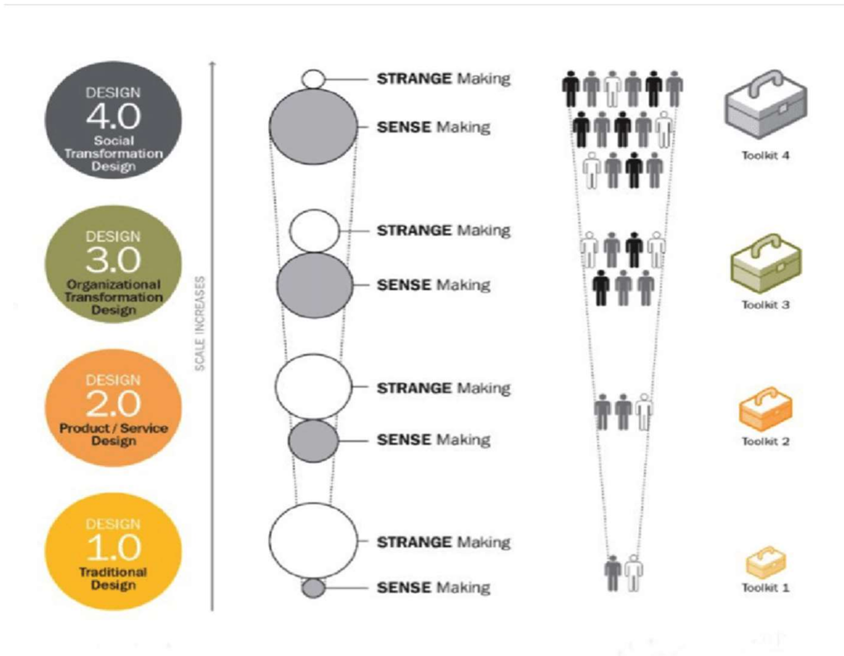


Fig. 2.1 Evolution of Design (Leonor et al., 2017)

2.1.2 Understanding the Concept of Design

Design is not merely an ornamental embellishment. It is the invisible thread intertwined with the fabric of our daily lives. It establishes a link between an idea and its material expression and inspires the adornment of objects with functional, aesthetic, and emotional values (Vitta and Nelles, 1985). To comprehend the significance of design, one must delve beyond its superficial allure. Design involves deliberately creating a tangible object, a process, or sometimes an experience (Kazmierczak, 2003). The architect Frank Lloyd Wright's Fallingwater is a perfect example of this concept. Wright did not merely conceptualize a building; instead, he designed a living environment that harmoniously merges with its organic environment, erasing the boundary between the interior and exterior. While situated at the top of a cascading waterfall, the cantilevered structure provides inhabitants with a functional shelter and awe-inspiring and breathtaking scenery (Hoffmann, 1993).

Additionally, design involves comprehending a user's requirements and developing a solution to meet those requirements. Consider Dieter Rams's sleek and understated creations; his Braun razor prioritizes aesthetics and user comfort, as evidenced by its elegant design and intuitive layout. This exemplifies that effective design encompasses aesthetics, functionality, and user experience (Ma Y. et al., 2022). The concept of design extends beyond the boundaries of physical products and processes. Currently, the design places a greater emphasis on creating experiences (Marcus et al., 2013). Observe the intuitive user interface of Apple devices, which Steve Jobs developed. He understood that a product's user experience surpasses technical specifications (Mao, 2021, August). Apple's products feature streamlined navigation, aesthetically pleasing appearances, and overall usability due to a rigorously crafted design philosophy that aims to generate feelings of joy and contentment in its users (Savvina, 2017). Design is utilizing its problem-solving capabilities to tackle crucial societal challenges. Bruce Mau, a highly acclaimed designer, advocates for the ideology of "Life-centered Design," a design philosophy that promotes applying design principles to address intricate issues in education, healthcare, and sustainability. Envision employing design thinking to develop educational programs that are both instructive and engaging or healthcare systems that are efficient and prioritize the needs of the patients (Bevolo, 2022)

Design is a multifaceted term that includes functionality, aesthetics, user experience, and societal influence. As seen in the influential works of Frank Lloyd Wright, Dieter Rams, Steve Jobs, and Bruce Mau, Design is an ever-changing discipline that continuously redefines its impact on molding our world.

2.1.3 Changing Dynamics of Design in Modern Society

The changing design dynamics in modern society indicate a fundamental transformation in our perception, creation, and interaction with the environment and many objects that influence our everyday existence. Design, previously a solitary pursuit concentrated on creating functional and aesthetically pleasing objects, is now experiencing an informative evolution in response to modern society's constantly shifting demands (Parsons, 2015). The change goes beyond aesthetics, integrating design into the core of our experiences and creating solutions for the most urgent concerns of the present time. This transformation in a design landscape requires thoroughly examining the concepts underlying these changes. An explanation is shown below.

- **The shift from physical products to immersive experience:** The transformation from focusing on products to experiences is a paradigm shift (Marcus et al., 2013). Website interfaces that were previously complex and unmanageable? However, now, we can consider the effortless process of reserving airfare through platforms such as Kayak. By considering intuitive interfaces, personalized recommendations, and integrated travel insurance options, reserving a trip is transformed from a tedious to a meticulously planned and enjoyable journey (Granados et al., 2008, January). Nike's flagship stores are another example of this change. They revolutionize the shoe-purchasing experience by integrating interactive displays, personalized consultations, and running tracks (Vos, 2018).
- **Design Thinking Addresses Real-world Challenges:** Modern design is applying its capacity for problem-solving to improve social welfare (Saurio, 2022). Consider Samsung Electronics's innovative work; they designed a new toilet and invented the "Lifesaver," a disposable, waterless toilet that does not require sewage or water systems. It explains the capacity of design thinking to tackle real-world problems

by enabling marginalized communities to enhance hygiene and sanitation by implementing user-centered Design (Samsung developed prototype).

- **Co-creation to promote sustainability and inclusion:** Design is increasingly acknowledged as an effective tool for tackling intricate problems and encouraging significant change (Nelson and Stolterman, 2014). Designers are expanding their scope beyond the conventional limits of their fields to address urgent concerns like sustainability, inclusion, and social justice. The change is propelled by a growing awareness of the interdependence of global problems, ranging from climate change and resource depletion to economic inequalities and social turmoil (Dominoni, 2024). Design is a dynamic concept that is continuously progressing. Initially focused on creating aesthetically pleasing and functional items, it has expanded to include developing immersive experiences, resolving problems, and promoting creativity for a broader range of people. With the continuous advancement of technology and evolving societal needs, the design concept will inevitably adapt and redefine itself, influencing the world in increasingly innovative ways.

2.1.4 The Impact of Design on Societal Development

Design, previously considered a domain of functionality and aesthetics, has transformed into a powerful influence that shapes societal development and advancement. This impact extends beyond the physical attributes of products; it involves all aspects of the user experience, shaping our interactions, behaviours, and, subsequently, the fundamental foundation of our societies (Mulder and Loorbach, 2016). Below are the impacts of design on society.

- **Advancing Efficiency and Innovation:** Effective design promotes innovation and enhances efficiency, moving societies towards progress (Utterback,2016). Consider the creation of the printing press by Johannes Gutenberg. This innovative design transformed communication and made knowledge accessible to all. Before the invention of the printing press, information was scarce and accessible only to a select few who held privilege. Gutenberg's innovative design, with movable type and an efficient printing process, facilitated the dissemination of knowledge to a broader spectrum of individuals, hence stimulating a significant increase in literacy rates, educational opportunities, and advancements in scientific exploration (Rees, 2006).
- **Design Shaping Behaviours and Interactions:** The design prioritizes creating user experiences that are functional but also appealing and meaningful (Benyon, 2019). Ride-sharing applications such as Uber or Ola have entirely transformed the transportation industry by providing a smooth and easy method of travel. The user experience, from initiating a ride request to monitoring its arrival, is deliberately designed to be intuitive and accessible. This alters our travel behaviours and influences urban design and traffic flow, ultimately impacting the functioning of cities (Rajesh, 2021).
- **Fostering Accessibility and Equitable Societies:** Design can improve accessibility and develop a more equitable society. Curb cuts, first intended to aid the mobility of wheelchairs, have a gentle incline from the sidewalk to the street (Agarwal and Sharma, 2014). Nevertheless, their advantages surpass that by a

significant margin. They facilitate enhanced accessibility for individuals with strollers, bicycles, and even shopping carts, fostering a more inclusive and user-friendly environment on our streets (Imrie and Hall, 2003).

- **Enhancing the healthcare system and promoting well-being:** Design Improving the healthcare system and promoting general well-being (Desmet and Pohlmeyer, 2013). In the past, medical gadgets were heavy and complex; however, the current glucose monitors are streamlined and user-friendly. These devices not only facilitate self-monitoring for individuals with diabetes but also enable people to assume responsibility for their well-being (Paul et al., 2012, March).

Design is not solely concerned with aesthetics; it is a powerful approach capable of significantly influencing societies. The importance of design on societal development is unquestionable, encompassing the empowerment of individuals, the enhancement of accessibility, and the influence on consumer behavior. However, current design developments encounter a few challenges.

2.2 Challenges in Traditional Design Development Practices

Traditional design development practices are experiencing significant challenges despite incorporating advanced technology at every step of the process. Although technology integration offers the potential for innovative concepts and improved productivity, it also poses notable challenges (Khan and Turowski, 2016). One challenge arises from the escalated utilization of resources and the production of waste linked to current development practices. This increased utilization of resources not only stresses limited environmental resources and worsens the ecological impact of design processes. As a result, the field is facing sustainability challenges that require evaluating methods to reduce environmental effects (Liedtke, 2014).

Furthermore, current design practices exclude some population groups, perpetuating disparities in their ability to access and engage with it. This leads to the emergence of inclusion challenges, compelling designers to prioritize equity and accessibility in their solutions (Polec and Murawska, 2021). When overcoming these challenges, the design community must carefully balance resource consumption with the population's need, with the urgent need for sustainability and inclusivity (see Fig. 2.2).

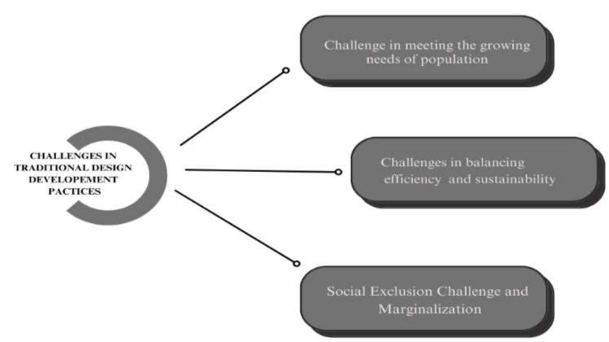


Fig. 2.2 Challenges in Traditional Design Development Practices

2.2.1 Challenges in meeting the growing needs of the population

The continuously growing human population significantly challenges traditional design development practices. Although technological advances have created opportunities for innovative solutions, there is a growing disparity between these practices and the capacity to address the requirements of a more significant population with fewer resources (Bongaarts,2009). The intricate issue arises from various crucial elements, such as resource limitations (Magdoff, 2013), waste production driven by consumerism (Glaubitz, 2012), planned obsolescence (Iizuka, 2007), and the continuously increasing demands of the population.

- The exponential increase in population is exerting significant pressure on the finite resources required for product advancement. According to the U.N. Population Division, the global population will reach 9.7 billion by 2050 (United Nations). This results in an ever-growing need for resources, posing a challenge for traditional design methods prioritizing functionality and usefulness rather than resource efficiency, making it difficult for them to keep pace (Gill, 2005). An alarming example is a report published in The Economic Times in 2019, which uncovered that the global production of garbage amounts to an astonishing 2 billion tonnes per year. Packaging alone contributes to 30% of this population (Bloomberg, 2019, July 12). The Ellen MacArthur Foundation's (2016) report shows that the existing approach of "take, make, dispose" is fundamentally unviable for a growing population (Ellen MacArthur Foundation, 2016).
- The problem is worsened by customer behavior influenced by marketing strategies and constantly evolving trends. Motivated by the belief that "new is better," consumers are increasingly attracted to the most recent and superior things, regardless of the adequate functionality of their current items. This relentless desire for newness reduces the lifespan of products and generates a significant amount of avoidable waste (Goodwin et al.,2008). According to a 2020 inspection from the U.S. Public Interest Research Group (US PIRG), smartphones now have a much shorter lifespan of only three years (US PIRG, 2020). This emphasizes the rapid speed at which products become obsolete, even before their intended end-of-life.
- Planned obsolescence is a deliberate strategy businesses employ to create products with a predetermined lifespan to promote repeated replacements. In 2022, a report by Reuters revealed that Apple deliberately reduced the performance of older iPhones, strategically encouraging users to purchase newer models (Reuters, 2022). These tactics substantially impact the continuously increasing waste issue and give rise to ethical problems regarding manipulating consumer behavior.

The combination of population expansion, limited resources, technological advances, consumer culture, and commercialization presents substantial challenges for traditional design development practices. These issues arise from higher resource consumption, waste generation, intentional product obsolescence, and prioritization of profit-oriented innovation instead of sustainable solutions.

2.2.2 Challenges in balancing efficiency and sustainability

Traditional design techniques prioritize functionality and aesthetics; they fail to consider the environmental impact of a product's life cycle (Vitta and Nelles, 1985). The linear "cradle-to-grave" model, which involves the design, manufacturing, usage, and disposal of items, substantially impacts the critical sustainability challenges: resource depletion and waste development (Jonsson and Mills, 2002).

The 2017 World Bank report on material extraction presents a remarkable identification: Worldwide material extraction has significantly increased since 1970, reaching an astonishing 92 billion tons. Every individual on Earth consumes approximately 12 metric tonnes of resources annually (World Development Report, 2017). The widespread consumption is driven by designs that favor initial affordability at the expense of long-term resilience, resulting in faster product turnover and a growing requirement for raw materials (Schaffner, 2013).

This unsustainable method is rapidly exhausting limited resources. According to a 2019 research report by the United Nations, indium, a crucial element in creating electronics, might be thoroughly used over the next ten years if current design patterns continue. This underscores the vulnerability of our dependence on limited resources for product design (Werner et al., 2015).

The conventional "take-make-dispose" approach creates significant waste (Ellen MacArthur Foundation, 2016). The global population produces more than 2 billion metric tons of municipal solid waste yearly. Developed nations frequently exhibit the highest levels of responsibility, as citizens in these countries generate a substantially more significant amount of garbage per person. Landfills serve as repositories for this trash, resulting in environmental contamination, deterioration of ecosystems, and the emission of detrimental greenhouse gases (Bloomberg, 2019, July 12).

The use of single-use plastics is an example of a design that is not sustainable regarding the environment. These widely used products, created for convenience without much consideration for their disposal, contribute substantially to the problem of plastic pollution in our oceans and landfills (Bloomberg, 2019, July 12).

2.2.3 Social Exclusion Challenge and Marginalization

The traditional design approach prioritizes innovation, efficiency, functionality, and utility and frequently overlooks the practical challenges people face at the bottom of the pyramid (BOP) (Pitta, 2008). The bottom of the pyramid (BOP) encounters substantial obstacles in obtaining and involving itself with design solutions. According to the World Bank, a staggering 4 billion individuals live on an income of less than $5.50 daily (World Bank Group, 2018, October 17). Prahalad (2005) depicts the global distribution of wealth as a pyramid, with a small number of affluent individuals at the apex and many impoverished individuals at the base, as shown in Fig. 2.3 (Prahalad, 2005). This oversight restricts progress and fosters inequalities, thereby creating challenges to social inclusion.

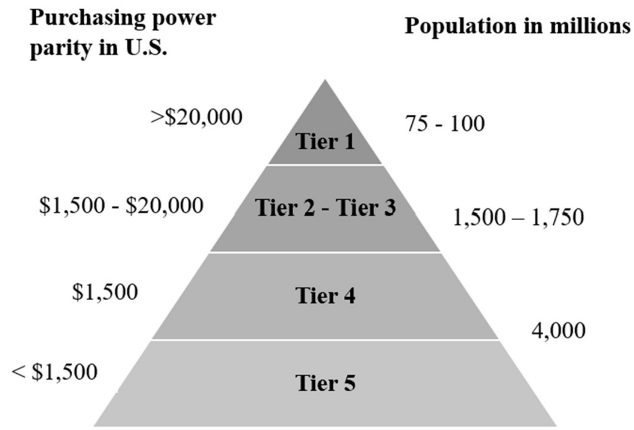


Fig. 2.3 The World Economic Pyramid

Traditional design approaches often prioritize the perspectives and preferences of dominant or privileged groups, neglecting the wide range of human experiences (Mendis, 2003). In addition, the products and procedures that result from these methods are often extravagant, making them inaccessible to marginalized communities (Friedline et al., 2020). Designers frequently target a user group with more significant resources and advanced technologies (Sondergaard and Hansen, 2017). This method fails to consider the specific constraints experienced by the BOP population, including low levels of literacy, restricted availability of the Internet, and dependence on alternative energy sources. Consider a sophisticated mobile banking application developed explicitly for smartphone users with reliable internet access but entirely unavailable for individuals residing in remote areas with basic feature phones and restricted access to energy (Simanis, 2012).

Moreover, economic factors sometimes influence design decisions, resulting in a focus on maximizing profit rather than prioritizing social impact. The emphasis on economic interests might lead to developing products and services that are too expensive or difficult for low-income individuals, thus perpetuating their exclusion from society (Rabbi, 2019).

There is a lack of business entities eager to enter the BoP market; the segment is considered unreserved or underserved. The absence of competition, limited market reach, large-scale operations, and streamlined supply chains result in elevated costs for an extensive range of products and services in the BoP sector, including credit, consumer banking, telecommunications, insurance, and even necessities like food and water (Simo, 2013). Marginalized communities consistently face a financial disadvantage in the marketplace due to their lack of wealth (Chikweche, 2013).

2.3 The Need for Frugality in Design Practices

The design certainly plays a vital role in shaping the growth of human societies (Kellaher, 2001); nonetheless, traditional design techniques frequently fail to address essential challenges like sustainability (Vitta and Nelles, 1985) and social inclusion (Rabbi, 2019). Therefore, a fundamental change has occurred, increasing frugality's significance in the design development process. Frugal design transcends ordinary cost reduction; it is an ethical perspective emphasizing resourcefulness, efficiency, and user-centricity, culminating in sustainable and effective products and services (Liefner et al.,2020).

Frugality in design provides the following effective solution.

- Frugal design prioritizes the utilization of minimal resources to optimize functionality. Functional products, modular design, and recycled or locally sourced materials are all potential approaches to this purpose (Weyrauch and Herstatt, 2017). A prime example is the foldscope, a fully functional microscope that can be magnified up to 140 times, suitable for scientific research and diagnosis. The device is modular with interchangeable lenses and components and can be easily compiled from flat paper sheets to ensure adaptability and user-friendliness. Additionally, recycled or standing materials, such as waterproof paper and inexpensive glass beads, are used to keep costs low and, at the same time, maintain environmental compatibility. This combination of functionality, modularity, and environmentally friendly materials makes FoldScope an effective device for global health and education initiatives (Das et al., 2021).
- Frugal design emphasizes accessibility by ensuring more individuals can obtain and utilize products and services. The Aravind Eye Care System in India employs established processes and affordable equipment to provide exceptional eye care services at a significantly reduced cost, enabling millions of individuals who would otherwise be unable to pay for it (Saqib and Mathu, 2024).
- Frugal Designs are designed for long-term use, emphasizing simple repair. This practice minimizes waste and prolongs product durability. The Fairphone company specializes in creating cell phones with modular components that can be readily replaced. This design approach promotes longer phone usage among consumers and minimizes electronic waste (Amanatidou and Gritzas, 2020).

Adopting frugal design contributes to creating a future in which design satisfies the needs of all while reducing its environmental impact. It is a transition from the belief that "new is better" and "more is better" to the understanding that "better with less" will result in a more equitable and sustainable global community.

2.4 Emergence of Frugality

The concept of frugality is not new; it has its roots in nature, where the optimal utilization of resources and minimization of waste are essential for establishing conditions that promote life and sustainability (McHarg, 1969).

2.4.1 Emergence of Frugality in the Natural World

The natural world is a source of inspiration for frugality due to the creativity and efficiency shown by its processes. Designers have turned to nature for inspiration in the early stages of product creation due to the increasing scarcity of resources and the growing need for innovation (De Pauw et al., 2010). Nature has already undergone evolutionary processes and successfully resolved many of its problems. Animals, plants, and other species have adapted to ensure survival and flourishing. The natural world has already successfully addressed the challenges that product designers, scientists, inventors, and philosophers attempt to resolve. Nature has spent millions of years making structures and mechanisms that work better than current technology, use less energy, and produce no harmful waste. Nature only uses the energy it needs and depends on the energy available for free. It recycles everything. It is resilient to disturbances. It uses form to determine functionality. The ongoing advancements in energy, aesthetics, ergonomics, materials, information, manufacturing, and packaging have been the fundamental universal measure of transformation that has effectively shown the frugal functioning of the natural world (Franklin, 2007). An analysis of how various elements of nature demonstrate frugality

- In current manufacturing processes that require high levels of heat and pressure, organisms such as spiders can produce robust silk fibers at average room temperature. Their layered methodology maximizes robustness while minimizing energy use (Benyus,1997).
- Abalone shells are a natural material that is twice as resilient as advanced ceramics due to their structure and chemical composition. This emphasizes biomimetic design's capacity to produce exceptional, sustainable resources (Benyus, 1997).
- The effective communication used by ants and bees to obtain food can serve as inspiration for developing algorithms that enable intelligent appliances to coordinate actions and cut energy usage (Benyus, 1997).
- Nature offers examples of effectively using renewable energy sources, from the energy-saving swimming method of the rainbow trout to the solar-powered energy generation of the oriental hornet (Benyus,1997).
- Hexagonal cells, which bees and wasps employ to optimize strength and space in their nests, are a principle that may be applied to a variety of buildings to maximize material efficiency (Benyus,1997).
- Beetle wings are composed of a natural material that can be folded repeatedly without harm. This motivates the development of sustainable packaging materials that are both flexible and durable (Benyus,1997).

2.4.2 Emergence of Frugality in Man-made world

The term frugality is derived from the Latin word 'frugal' (frugalis) of the mid-sixteenth century, which signifies being thrifty and modest (Soni and Krishnan, 2014). It harkens back to ancient periods when economic resources were lacking. It applies equally to today's growing economies, such as India and China, where comparable situations persist (Roiland, 2016). According to the Oxford Dictionaries, the term 'frugal' is defined as being "simple and plain, and costing a small amount" and "using only the necessary amount of money or food." However, in a literal sense, 'frugal' refers to utilizing minimum resources, which leads to significant savings of those resources (Dictionary, 2020). In this context, Frugal Design is about producing affordable products tailored to meet the specific requirements of consumers in developing countries. This strategy emphasizes using resources efficiently and creating sustainable technology. Its ultimate goal is to benefit society by ensuring that limited resources are used responsibly to preserve them for future generations (Tiwari and Herstatt, 2012). The population is expected to continue expanding in the future, and since resources are limited, innovations that consider these factors are urgently needed. The factors mentioned above primarily pertain to the extraction of resources and the manufacturing process of a product (Horn and Brem, 2013). Frugal design extends beyond these aspects; It also considers optimizing consumption through enhancements in the quality, price, and lifespan of products and material resources (Roiland, 2016).

Frugal design emergence in the man-made world across several significant domains:

- During World War 2, Britain adopted frugal design in theory and practice to solve the widespread scarcity of resources. In 1941, the Utility program, implemented by the British Board of Trade, intended to provide high-quality consumer products at affordable rates. The concept was initially used in clothing and subsequently expanded to furniture, with the frugal concepts acquired and implemented being extended to numerous other consumer products. The civilian program restricted the utilization of surplus resources and specific chemicals and substances, such as wool, essential for producing military clothing (Bayley, 2011). The frugal mindset manifested in what was considered excellent design and style, focusing on high efficiency and quality, while still being affordable and accessible to all segments of the British population (Mason, 2011). Implementing austerity measures imposed certain dress limitations, including a maximum of two pockets, five buttons, six seams in a skirt, two inverted or box pleats or four knife pleats, and no more than 4 meters of stitching. British society contributed value by addressing challenges associated with limited resources, which affected every aspect of the value chain, including the availability of raw materials and trained workforce, as well as the design and maintenance of finished products. The problem-turned-opportunity arises from the necessity to i) conserve valuable resources. ii) It is crucial to enhance manufacturing efficiency due to the departure of skilled labor for military service. iii) It is essential to address the issue of rising prices to ensure that the civilian population can afford excellent products (Clouting, 2018).
- Henry Ford's implementation of the assembly line and the Japanese lean processes are notable instances of frugal design. Henry Ford's practical perspective and a strong emphasis on cost reduction, waste reduction, and productivity led to significant job growth and market expansion (McCloy et al., 2010). Japan's success story after World War II is attributed to its emphasis on frugal thinking and design in products and processes. Due to a scarcity of natural resources, limited international access, and constraints in space and funds, Japanese companies questioned and revolutionized the basic principles of manufacturing. They introduced widely recognized ideas such as lean production, timely production, constant enhancement, minimization, and kaizen (Womack et al., 1990).
- The first global scholarly appearance of the frugal design was published in a book about strategy in China by Anil K. Gupta and Haiyan Wang (2009) (The Economist. (2010a, April 15th). Subsequently, this was succeeded by The Economist, which published a comprehensive article in 2010 titled "First Break All the Rules: The Charms of Frugal Innovation." In 2011, Marco Zeschky, Bastian Widenmayer, and Oliver Gassmann published a journal article to elucidate the idea and concept of frugal design. They defined frugal design as affordable, sufficient quality products that originate in the needs of emerging markets (Zeschky et al., 2011). In 2009, the

Frugal Innovation Lab at Santa Clara University set up the first real-world test of frugal Design (Woolridge, 2010). Frugal innovation is sometimes referred to as juggad and reverse innovation (Govindarajan and Trimble, 2012). A book on Jugaad was the first and most thorough look at this associated phenomenon and ideas. A frugal innovation book followed it (Rajdou et al., 2015). It has been nearly a decade, and scholars are still trying to assemble all the different meanings, understandings, and approaches.

- The typical challenge with resources in emerging markets is that customers are highly value-conscious; many have recently converted from non-consumers to consumers. Local businesses in emerging countries are developing innovative products, which are then sold globally (Prabhu,2017). Prominent frugal innovators, whose products provide superior customer value at low prices, have increased, particularly in Chinese and Indian corporations. In 1996, the Chinese company Haier created the Mini Magical Child washing machine for the regional market. It provided a viable substitute for extensive, costly washing machines for small daily loads and is now sold worldwide (Zeschky et al., 2011).
- The significance of frugal design is expanding beyond emerging markets and is becoming more widely acknowledged internationally due to concerns involving austerity measures and the worldwide recession (Escudero-Cipriani et al., 2024). Many of today's frugal innovators strive to overcome the lack of resources, skills, and ability to fulfill needs by providing economical, high-quality solutions. Ensuring the provision of essential services to all individuals in developed nations is becoming ever more complex and challenging in a sustainable manner. The current state of the global economy is characterized by low levels of financial liquidity, significant reductions in public spending, record-high levels of public debt, scarcity, and increased demand for natural resources, leading to higher prices and decreased consumer spending. Western companies must seek frugal expansion methods with limited resources (Ashfaq et al., 2018). Companies embrace frugality during periods of reduced revenue due to a recession or when profits are squeezed due to increased competition. G.E.'s approach involves prioritizing frugal design in emerging economies. G.E. strategically targets emerging countries as the initial market for introducing new applications or segments to expand into developed countries (Davidson, 2015).

2.5 Objective, Definition, and Principle of Frugal Design

This section examines the fundamental objectives of frugal design, presents comprehensive definitions, and guiding principles that influence approaches to creating efficient, integrated, and sustainable solutions.

2.5.1 Objectives

The key objectives of the frugal design concept are listed below.

- Frugal design delivers more value with fewer resources (Prabhu, 2017). It emphasizes the development of cost-effective and easily accessible products and services for all users by utilizing affordable and simple technologies and design ideas (Singh et al., 2020).

- Frugal design transcends the concept of affordable alternatives. The objective is to develop comprehensive solutions that positively impact business performance, user experience, and process efficiency (Hindocha et al., 2021).
- Frugal design promotes sustainability and resolves global problems such as social needs, environmental conservation, and economic growth (Albert, 2019).
- Frugal design highlights the importance of simplicity in the products, manufacturing processes, and business strategies. It strives for increased efficiency with fewer resources without sacrificing quality (Lim and Fujimoto, 2019).
- Frugal design facilitates the democratization of the innovation process and empowers enterprises with minimal resources to create innovations for low-income consumers. It enables relatively small businesses to innovate despite limited resources (Khubisa, 2017).

2.5.2 Definition

Frugal design (F.D.) has gained considerable interest and implementation in various sectors worldwide, including healthcare, manufacturing, food, automotive, energy, and academics, since its introduction in The Economist in 2010. Nevertheless, with its increasing popularity, the frugal design concept has been explained with many definitions, predominantly through case studies.

Table 2.1 The following are definitions of the frugal design concept

Author, Year	Definition
(Gupta, 2011)	Frugal design is an emerging management philosophy that begins with the specific requirements of the lowest market segments of the pyramid and proceeds in reverse to devise suitable solutions. These solutions may differ substantially from those currently in place, as they are tailored to cater to the needs of higher market segments.
(Brem and Wolfram, 2014)	Moderate sustainability, low to moderate sophistication, and moderate focus on emerging markets.
(Koerich and Cancellier, 2019)	Frugal design can cater to customers in all economic segments who prioritize cost or seek products that effectively fulfill their needs.
(Ratten. 2019)	The cost-effective utilization of products and services developed when resources are limited.
(Angot, 2015)	Good enough solutions that utilize limited and cost-effective resources to address the shortage of resources.
(Agarwal and Brem, 2017)	Frugal design refers to developing good enough low-cost products to meet the needs of consumers with limited resources.
(Agnihotri, 2015)	Frugal design pertains to creating products and services within the limitations of available resources.

(Kuo,2014)	Frugal designs are goods and services that prioritize fundamental demands, minimize resource use, and eliminate unnecessary features during the design process.
(Sharma and Iyer, 2012)	Frugal design arises from a lack of resources, where few resources are used to fulfill the requirements of low-income consumers.
(Zeschky, 2011)	Addressing significant resource limitations by developing products that offer substantial cost benefits compared to current options. 'Products that are of satisfactory quality and affordable, catering to the requirements of consumers with little resources.
(Zeschky et al., 2014)	Frugal design consists of products or services that are designed for particular applications in environments with limited resources rather than being re-engineered solutions. • Technical innovation • Market innovation • Market-oriented, not product or service-oriented.
(Hossain, 2016)	Frugal design encompasses developing products, services, or combinations that are cost-effective, environmentally friendly, user-friendly, and have been created in response to limited resources. Frugal innovations are typically designed for and within low-income market environments and are considered distinct from inventions in developed markets.
(Tiwari R, Herstatt, 2013)	Defined by its cost-effectiveness, durability, ease of use, flexibility to adapt to different scales, and appealing value proposition.
(The Economist, 2010)	Frugal design encompasses more than product development; it necessitates a complete rethink of manufacturing processes and business structures.
(Weyrauch and Herstatt, 2017)	Frugal design consists of three characteristics: a significant reduction in cost, a focus on core functions, and an optimal level of performance.
(Soni and Krishnan, 2014)	It is efficiently accomplishing the intended goal while maintaining cost-effectiveness.
(Basu et al., 2013)	It prioritizes the requirements and circumstances of individuals in developing countries. Its goal is to create services and products that are suitable, flexible, economical, and easily accessible for growing markets.
(Rao, 2013)	Scarcity-induced, reverse innovation, or minimalist Frugal design involves minimizing resource usage and focusing on simple products and services while occasionally incorporating advanced technology, which has significant potential for promoting sustainable development.

(Bound and Thornton,2021)	Frugal design is characterized by its superior performance compared to alternative approaches and their potential for large-scale availability.
(Bhatti YA, Ventresca, 2013)	The goal of frugal design is to accomplish more with fewer resources for a more significant number of individuals.
(Bhatti et al., 2018)	Accomplishing more with fewer resources for the benefit of many.
(Simula, 2015)	A product, service, or solution that emerges in the face of resource constraints—financial, human, technological, and otherwise—and that, when completed, is less expensive than competing offerings (if available) while still satisfying the needs of unmet customers

Gupta argued that 'Frugal design is an emerging management philosophy that begins with the specific requirements of the lowest market segments of the pyramid and proceeds in reverse to devise suitable solutions. These solutions may differ substantially from those currently in place, as they are tailored to cater to the needs of higher market segments (Gupta, 2011). Brem and Wolfram shared the same understanding, defining F.D. as having Moderate sustainability, low to moderate sophistication, and moderate focus on emerging markets (Brem and Wolfram, 2014). (Koerich and Cancellier(2019) insisted that It is noteworthy that those with a frugal design are not limited to markets in low-income countries; instead, they are present in marketplaces in higher-income countries as well (Koerich and Cancellier, 2019)

(Angot, 2015) described F.D. as 'Good enough solutions that utilize limited and cost-effective resources to address the shortage of resources. This overlaps with many other definitions, such as 'Frugal design refers to developing good enough low-cost products to meet the needs of consumers with limited resources (Agarwal and Brem, 2017). Frugal design pertains to creating products and services within the limitations of available resources. Agnihotri, 2015) and Frugal design arises from a lack of resources, where few resources are used to fulfill the requirements of low-income consumers (Sharma and Iyer, 2012). Zeschky et al. (2011) defined F.D. as addressing significant resource limitations by developing products that offer substantial cost benefits compared to current options. Products of satisfactory quality and affordability cater to the requirements of consumers with few resources. Both definitions emphasize costs, with minimal functionality aimed at users with limited resources (Zeschky et al., 2011). According to Hossain (2016), Frugal design is commonly associated with innovation that originated in low-income countries. However, it is relevant and applicable to both emerging and developed economies, as it aims to reach individuals at the base of the economic pyramid (Hossain, 2016).

A substantial body of literature related to F.D. establishes connections with sustainability concerns; however, the analyses of these connections may vary. Several experts contend that F.D. can promote a more sustainable world (Albert,2019) and development (Basu et al., 2013). While some argue that F.D. does not generate a lasting impact, is not inherently sustainable, and may not be environmentally benign from the start (Weyrauch and Herstatt, 2017), see Table 9.1.

2.5.3 Principles

In 2015, Navi and Jaideep, Proposed a set of six principles for implementing frugal design in an enterprise or creative community, as shown in Table 2.2.

Table 2.2. Frugal Design Principles

Principle	Description
Engage and Iterate	The first principle is to engage, and iterate (EandI) explains; instead of having separate research and development (R&D) departments that presume what customers want, EandI starts with customers and observes how they act in their natural environment. It then considers how products can be made as helpful as possible, going back and forth between the customer and the lab to improve designs.
Flex Your Assets	It provides information about changing customer preferences, indicating a growing desire for customized products and services that meet unique needs and preferences and are accessible at their leisure. The shift towards mass customization is causing significant changes in operational and supply chain processes. This is achieved through advanced technologies like robotics and 3D printers and novel methods such as social manufacturing and continuous production. These developments enable operations and supply chain managers to improve flexibility in production, logistics, and service delivery, allowing them to meet the expectations of demanding customers more efficiently and cost-effectively. The objective of asset flexing is not solely focused on conserving resources, such as reducing inventory, but also on conserving time (a corporation's most valuable asset).
Create Sustainable Solutions	It illustrates how businesses can adopt sustainable methods, such as the "cradle-to-cradle" approach, which involves continuously recycling components and materials to create waste-free goods.
Shape Consumer Behaviour	It demonstrates to organizations how to enhance consumer empowerment and a sense of riches by promoting conscious decision-making. Marketing managers may create products and services that match the ideals and goals of consumers by comprehending their psychology and behavior. This results in a mutually beneficial situation: customers experience contentment and financial stability, while corporations establish customer loyalty and increase their market share by effectively positioning and communicating the desirable advantages of these cost-conscious solutions.
Co-create Value with Prosumers	As this principle shows, companies' most proactive customers are their prosumers, who can help them come up with new ideas, test and develop them into products and services, and get them on the market faster, better, and with more help.

	Companies can involve other outside parties, such as suppliers or distributors, competitors, or other businesses, to save money.
Make Innovative Friends	Indicates that R & D and operations managers can enhance the efficiency of developing frugal goods, services, and business models by collaborating with external partners (such as suppliers, universities, venture capitalists, and start-ups) rather than working independently.

2.6 Frugal Design as a Design Approach

Frugal design is a strategic problem-solving method that prioritizes producing the highest possible value while using the fewest resources. It involves designing and delivering processes, products, and services that maximize their effectiveness, affordability, and accessibility for the most vulnerable users. At its essence, the frugal design focuses on doing more with fewer resources in creative ways to achieve the objectives more quickly and affordably than would otherwise be feasible. Frugal design aims not solely to produce affordable solutions but to develop comprehensive solutions that benefit customers' well-being and business efficacy. The foundation of frugal design approaches is their emphasis on comprehending user requirements before commencing the design process. Innovators must understand users' requirements for a product or service to effectively find opportunities for less resource consumption without compromising quality or the user experience. Innovators can effectively match resourcefulness strategies with user expectations and experience goals using a user-centric strategy. This ensures the resultant solutions remain viable and attractive to the target audience. Nevertheless, it is essential to acknowledge the constraints associated with existing frugal design methods. The intense concentration on fundamental needs can occasionally neglect the user's inclination for visual appeal or a sentimental attachment to the product. Moreover, frugal solutions frequently succeed by addressing specific requirements in a specific setting. Scaling up the manufacture of these products or modifying them to suit various contexts might pose significant challenges. Ultimately, there is a challenge in how anything is seen. The emphasis on affordability might occasionally create the impression of inferiority, even while the product fully functions.

2.7 Frugal Design and Overlapping Terminologies

Despite extensive research on innovations for resource-constrained environments, the field of frugal design encounters a terminology challenge. Although significant progress has been made in developing solutions that effectively utilize restricted resources, often referred to as "resource-constraint-based innovations," a challenge arises due to the inconsistent terminology used to express similar concepts (Von Zedtwitz et al., 2015). Table 2.3 is provided to clarify these similar terminologies. This table would serve as a valuable tool for comprehending the distinct disparities among these terms. By explaining the vocabulary, we may progress with this helpful design approach and its potential for a more inclusive and sustainable future.

Table 2.3 Frugal design and overlapping terminologies

Author, year	Terminology	Explanation
(Radjou et al., 2012)	Jugaad	These represent improvised solutions and approaches devised to address problems arising from marginal contexts, typically by individuals within those contexts. The insights derived from Jugaad innovations have been translated into organizational applications by Radjou et al.
(Witell et al., 2017)	Bricolage	An inclination and perspective that prioritizes resource frugality in the development of cost-effective solutions for marginalized contexts. Entrepreneurship in marginal contexts is the focus. Comparable to Jugaad.
(Gupta, 2010).	Gandhian Innovation	It is an amalgamation of Gandhian philosophy with innovation theory. Solutions adapt technologies developed by people and scale them to serve a large population in MC. They are semi-philanthropic, focused on scaling local technology to serve the masses.
(Hossain, 2016).	Grassroot innovation	It is a method for devising solutions in marginal contexts in collaboration with creative individuals. Innovative concepts generated by individuals are modified and methodically expanded to become commercially viable products that cater to a broader consumer base.
(Gundry et al., 2011)	Catalytic innovation	A strategy that prioritizes the creation of societal transformation by disrupting established marketplaces. The emphasis is on establishing networks and infrastructures that serve as catalysts to facilitate innovative solutions in marginalized environments.
(Chen,and Shen, 2023).	Resource constraints innovation	This method is utilized in marginal contexts when limited resources are needed to generate innovative solutions. The approach prioritizes the development of cost-effective, mass-market solutions while harmonizing performance and cost objectives.
(Markides, 2006)	Disruptive innovation	Innovative solutions can disrupt the current market participants by offering solutions that outperform existing ones while being much more cost-effective.
(Govindarajan and Trimble, 2012)	Reverse innovation	Innovation solutions have predominantly been created for or inside emerging markets and are then marketed and sold in industrialized countries, owing to their distinctive and significant value propositions.

2.8 Relationship between Frugal Design, Sustainability, and Inclusion

The design field is experiencing a significant upheaval, with an increasing focus on developing practical solutions, conscious of resource constraints, and considering societal influence (Bouckaert et al., 2011). Due to these concerns, frugal design has emerged as a philosophy that forms the basis of the threefold combination of sustainability, inclusivity, and responsible innovation (Brem and Ivens, 2013).

The frugal design emphasizes resource conservation. It promotes simplicity, focusing on giving basic functionality and avoiding unnecessary complexity. This results in products that utilize less material, energy, information, space, and time to produce more value for users. For example, the Lifestraw water purifier utilizes optimal resources (i.e., filter and straw) to offer safe drinking water in developing nations. Durability is another crucial aspect of inexpensive design. Developing longer-lasting products lessens the environmental effect of repeated production cycles and the waste generated from regular replacements (Walters, 2008).

Sustainability concepts are easily aligned with frugal design, emphasizing resource efficiency. It reduces resource consumption, which benefits the environment. A frugal strategy reduces emissions, consumes less energy, and produces less waste. As the most efficient use of available resources, frugal design frequently leads to reduced production costs. Because of their cost, sustainable solutions are more widely available, especially in low-income areas. i.e., a solar lighting system built using easily accessible components and a streamlined building procedure. Those who might not otherwise be able to afford clean and renewable energy solutions can profit from it (Trompette and Cholez, 2023).

Beyond affordability, there is a broader link between inclusivity and frugal design. A more straightforward design can be more flexible. It is easier to adapt products with more straightforward features to meet the needs of a broader range of users. An artificial limb (Jaipur knee) is made of modular parts. This ensures inclusivity for users with varied physical restrictions by enabling modification depending on individual requirements. Local communities can be empowered through frugal design. It promotes economic development and self-reliance by using locally skilled labor and easily accessible materials in the production process (Ceri, 2013).

This makes modification possible based on specific needs, guaranteeing inclusivity for users with different physical restrictions. A communal biodigester made with resources and building methods found around. This generates local skills and jobs and offers a sustainable waste management solution.

Being frugal means using less and producing something that has a more significant impact. It creates a design ethos that benefits both the planet and people by bridging the gap between inclusiveness and sustainability (Albert, 2019). Frugal design can create a future where responsible innovation propels positive change by encouraging resource efficiency, creating long-lasting products, and making sustainable solutions accessible. Adopting this strategy is essential to building a more just and ecologically mindful society.

2.9 Research Gaps

Several research gaps identify various limitations of frugal design practice that make integrating a product with frugal design challenging. The following are the gaps found in the literature.

2.9.1 Universal understanding of the Frugal Design concept

The term "frugal design" has become popular, yet it is usually connected to a specific geographical region (emerging countries) or socioeconomic (Bottom of the Pyramid) group. Having a universal understanding of frugal design may be difficult. The meaning and conceptualization of frugal design have received insufficient attention (Hindoch et al., 2021). This limits its global applicability, adaptability, and potential for broader application (Hossain, 2018). This more profound comprehension of frugal design, with its innate focus on resource efficiency, can foster sustainable development and advances in various sectors.

2.9.2 Frugal Product Adoption: Social Stigma

The social stigma associated with products designed for marginalized communities constitutes a significant barrier to the widespread adoption of frugal solutions. This prejudice effect may manifest as feelings of inferiority or embarrassment, leading individuals to resist adopting the product and instead opt for alternative solutions, even when such alternatives are less valuable or more costly. McMurray et al. (2019) illustrated that marginalized people may not choose to use frugal products due to the social judgment attached to them. This undermines the design's efficacy and perpetuates the inequities the product seeks to address.

2.9.3 Standardized matrix for frugal design

Existing research is limited to defining frugal design as a low-cost design. This ambiguity leads to a significant gap. The design community lacks a standardized matrix for objective assessment and benchmarking frugality in various products, processes, and systems.

2.9.4 Environmental Impact of the resource-intensive production process

The production process of the product, characterized by high material and energy consumption, poses a significant threat to the built environment (Bostrom, 2023). Unsustainable practices, such as using virgin materials with embodied energy for short-term cost reductions, lead to unfulfilling desired sustainable outcomes (Omer, 2009). The UN Environment Programme (UNEP) research on resource efficiency highlights how this mix of factors leads to resource depletion, air and water pollution, and environmental deterioration, ultimately resulting in the loss of essential resource bases.

2.9.5 Social stratification and social inequality

High-cost Manufacturing processes lead to social stratification and inequality, which in turn causes a sizeable social divide. Costly production frequently results in higher product pricing; according to Shavitt et al. (2016), this prevents low-income populations from obtaining necessary goods and services. Goldsmith et al. (2014) demonstrate how lower-income groups' access to technologically advanced commodities is restricted by their premium pricing, exacerbating economic inequality.

2.9.6 Assessment method for measuring design frugality

Literature about assessment methods for measuring design frugality is lacking. Prior studies have primarily examined the social dimensions of frugality. Nevertheless, all-encompassing criteria are needed to evaluate frugality from a broader perspective, including its social one. For example, although academics such as Prahalad and Mashelkar (2010) have written extensively about the advantages frugal innovations bring to society, including accessible medical gadgets for low-income people, the frugal design attributes that make these breakthroughs frugal frequently fail to be recognized. Furthermore, research by Bhatti et al. (2017) emphasizes the value of frugal design in developing affordable solutions for developing markets. Still, a systematic way to evaluate how frugal these designs are needs to be offered. Creating these kinds of evaluation techniques would close this crucial gap and improve the efficacy of frugal design in various industries.

2.10 Objective and scope of work

This research aims to develop a frugal design framework that prioritizes the efficient use of resources to develop user-centric solutions. The following objectives are to achieve this aim.

- To Redefine Frugal Design: Develop standardized, generally applicable definitions of frugal design that prioritize sustainability and social and economic inclusion beyond regional or context-specific interpretations.
- To identify the attributes of frugal design: Determine frugal design's measurable attributes, allowing quantification and assessment of frugal design's effectiveness.
- To develop a Frugal Design Evaluation Model (FDEM): Develop a structured evaluation model to quantify the product's efficiency and systematically measure the degree to which the existing products align with frugal design criteria.
- To investigate the root causes of product inefficiency throughout the lifecycle: Analyze the product lifecycle and identify factors hindering compliance with frugal design and production criteria. This leads to inefficiency and unsustainable outcomes.
- To develop and validate the frugal design framework: Develop an input-output (IO) frugal design framework that optimizes resource utilization in the design processes to enhance sustainability, performance, function, and inclusion of the design solutions.

2.10.1 Scope of the Research

The development of an inclusive and sustainable framework for frugal design is the primary goal of this research. It accomplishes this by taking inspiration from the practical and flexible solutions in nature. The scope covers the following areas:

- Identify Frugal Design Attributes: The research delves into the essential attributes that make frugal design practices successful. This entails reviewing prior literature and interacting with experts.
- Users' Perspectives: The research investigates the opinions of various users on the idea of frugality and how it is applied to design. This helps to make it easier to determine how to create frugal design solutions that satisfy the demands of all users.
- Develop a frugal design evaluation model (FDEM): A method to evaluate the degree of frugality attained in a design solution; designers can use this model to assess their products and pinpoint areas that need improvement.
- An Input-Output frugal design framework: The research has developed an input-output (IO) frugal design framework, a structured approach to optimizing resource utilization in a variety of design processes, particularly for resource-related or sustainable dedicated projects. The aim is to optimize development by focusing on

critical inputs, maximizing valuable outputs, simplifying complex systems, and enabling effective value-added technologies.

- Foster inclusivity under resource scarcity: The research examines user preferences and behavior patterns in environments with limited resources. This allows us to better understand how to create resource-efficient, inclusive solutions that meet the needs of a wide range of users.

2.11 Summary

An extensive literature review of relevant works in frugal design is presented in this chapter. It covers all research on various topics, such as the definition and development of design, the difficulties encountered in the field, the necessity of frugality in design, and the rise of frugality philosophy. The chapter delves into frugality in design, emphasizing themes that overlap significantly. This review assists in defining the objectives and scope of the work done in this research and points out research gaps in the field.

Chapter 3

Redefining Frugal Design

"To define a thing is to substitute the definition for the thing itself."- Georges Braque.

The "frugal design" concept has become popular, but it is usually connected to a specific geographical region (emerging countries) or socioeconomic (Bottom of the Pyramid) groups. Having a fundamental, uniform understanding of frugal design may be difficult. The meaning and conceptualization of frugal design have received insufficient attention (Hindoch et al., 2021). This limits its global applicability, adaptability, and potential for broader application (Hossain, 2018). Adopting a more comprehensive perspective that may facilitate cross-disciplinary and cross-class learning and using the full range of frugal practices is essential. This more profound comprehension of frugal design, with its innate focus on resource efficiency, can foster sustainable development and advances in various sectors. This chapter focuses on redefining the frugal design.

3.1 Introduction

With the recent surge in publications, Frugal Design (FD) has undoubtedly introduced a new sense of vitality into conceptual and empirical research (Tiwari et al., 2016); however, the concept is socially created based on diverse domains of knowledge, and many uncertainties about its conceptualization and theorization remain unresolved (Arshad et al., 2018). What are the attributes of FD, and how do these attributes relate? Without an adequate understanding of the fundamental attributes of FD and its rationale? (Singh et al., 2020). These underlying structural barriers may hinder the consistency of the concept and prevent its interactions with other domains (Bencsik, 2016).

This research is motivated by observing varying descriptions or definitions of FD, leading to hype and buzzwords in scholarly research. In contrast, the meaning and conceptualization of FD have received insufficient attention. Without a comprehensive definition of FD, academics and practitioners will be unable to advance the concept in the future (Hindoch et al., 2021). Practitioners in diverse industry groups use the phrase FD inconsistently to represent a business model (Hossain, 2021), an innovation based on the scarcity of resources (Woschke et al., 2017), Jugaad (Radjou et al., 2012), Bottom of Pyramid (BOP) Design (Heeks, R., 2012), and Cost Innovation (Williamson, 2010). Whereas current existing literature shows varying degrees of research interest amongst researchers in this field, it is evident that a comprehensive understanding of the FD concept is lacking (Hindoch et al., 2021), and Inconsistencies in the existing literature (Bhatti et al., 2013). The researcher and practitioner struggle with the difficulty and complexity of understanding this concept, as they do not share a uniform view of the FD concept, which leads to a misunderstanding of its essence (Hossain, 2018).

A fundamentally uniform understanding of FD can only be developed through a solid sense of the primitives and linguistic clarity of FD. This research employs a qualitative technique with an integrated brief professional survey, which empirically addresses the main research challenges using a seven-step theoretical approach and a three-level analysis. The research developed a cohesive definition of "Frugal Design" to distinguish it from overlapping terms (e.g., BOP, Jugaad, Cost innovation, etc.)

3.2 Research Approaches and Procedures

The design research is critical in determining how it should be conducted. Researchers can make a methodological decision if they comprehend the design choices and methods. There is a continuous ontological debate over the nature of the FD concept (Tesfaye and Fougère, 2022). The most effective approach is to address the existing gap in providing a comprehensive overview of the issue of lacking an overview of FD's core attributes. As a result, the research used a pragmatism paradigm to address the ambiguous challenges of FD. The research utilized an embedded design with preliminary data collection and secondary data analysis. It proposed a Seven-step method based on an in-depth qualitative examination of existing FD definitions in the literature. The research suggests an approach that combines previously established guidelines. These guidelines were established to enhance this approach's scientific rigor and tackle several inadequacies. An FD definition was developed through three stages: collection, analysis, creation, and evaluation, as shown in Fig. 3.1.

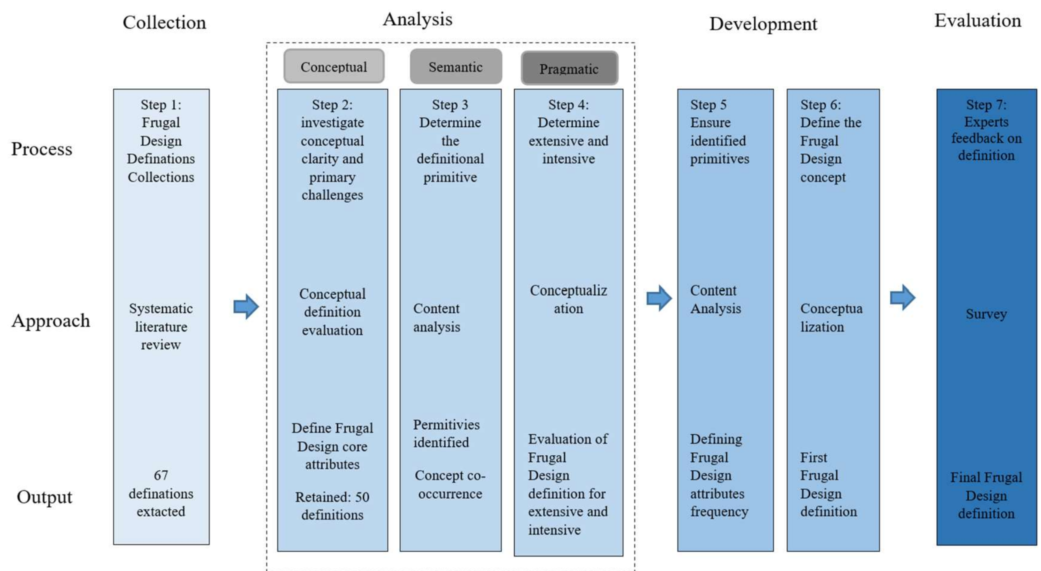


Fig. 3.1. Research procedure

3.3 Development of Frugal Design Definition

The following section covers developing the definition of frugal design and the challenges that must be considered in the existing definitions.

3.3.1 Collection: Frugal Design Definitions

Developing a definition of FD requires a clear understanding of how the concept has been discussed in previous research. Collecting and synthesizing existing definitions from the literature is an essential initial step in formulating a comprehensive definition

Step 1: Frugal Design Definition Collection

A systematic literature review (SLR) of FD definitions from established databases was undertaken to minimize random errors and mitigate potential bias (Ophoff et al., 2014). The PRISMA standards (Preferred Reporting Items for Systematic Reviews and Meta-analyses), relevant publications were identified as shown in Fig. 3.2. The initial outputs from searching for "Frugal Innovation," "Frugal Invention," "Frugal Design," "FD," and "Frugality" in the research databases, a total of 511 articles were retrieved, i.e., ABI/INFORM Complete 63, Emeralds 49, EBSCO 32, IEEE Explore 15, Inder Sciences 2, Scopus 44, Science Direct 99, Sage Premier 30, Taylor and Francis 70, Web of Science 63, and Wiley 44. To meet FD and quality standards, the research focused on peer-reviewed articles. Since 2000 was the first year FD was used in the literature, article searches were limited to 2000-2023. English articles were chosen to avoid misinterpretation of the inclusion and exclusion criteria. 149 duplicate articles from well-known databases were removed throughout the search. Additionally, 43 of 362 items were deleted because they were outside our assessment scope. Filtered articles had "frugal innovation", "Frugal design" in their titles and abstracts. The investigation found 121 duplicate records. We checked the remaining abstracts and bodies to see if any highlighted frugal innovation, and frugal design using other wording, led to 29 more articles. Only 67 of 76 FD definitions in the literature have been evaluated. Remove the definition that acknowledges other writers (Fig. 3.2). The following section analyzes the definitions.

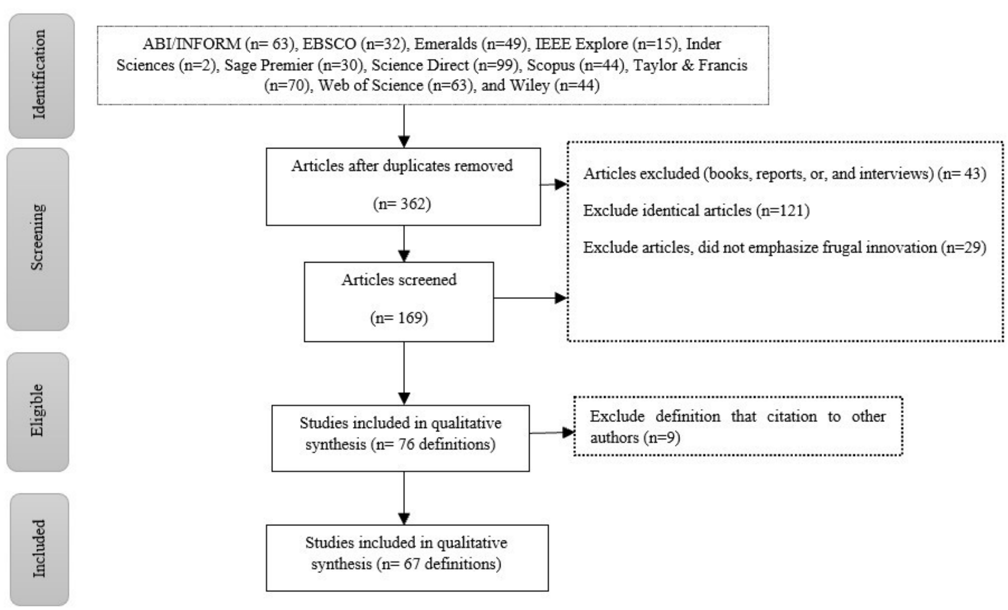


Fig. 3.2 PRISMA process

3.3.2 Analysis: Frugal Design Definitions

3.3.2.1 Level 1: Conceptual analysis

The study commences with a conceptual analysis of definitions. First, definitions are conceptually analyzed. This requires following Suddaby's (2010) criteria for conceptual definition and clarity guidelines. This analytical approach was employed to systematically evaluate and ensure the accuracy and comprehensibility of the definitions under consideration.

Step 2: Investigate conceptual clarity and primary challenges

Each definition was examined to evaluate its conceptual clarity and identify its essential components. We discovered two major challenges: attribute conflation and conceptual stretching.

Challenges: Attribute conflation and concept stretching

The conflation of characteristics representing various dominant aspects, with characteristics expressing various dominating aspects, violates conceptual logic (Yuan and Tao, 1999). A review of literature indicates that two widely cited definitions fail to clearly distinguish between frugal design as a concept and its effect. Table 3.1 shows the First group's of definition of FD: “The degree to which customers' capacity to get and innovatively use economic resources can be used to procure long-term objectives.” (Lastovicka,1999) and the other group (see Table 3.2) defined FD as “It is the process of (re)designing goods and services to substantially lower costs while maintaining user value to reach a wide number of consumers, especially low-income individuals.” (Tiwari and Herstatt, 2012). Both definitions emphasize the product's reduced cost and the intended customer. Other related FD definitions: “It is not re-engineered solutions; rather, they are goods or services made for extremely narrow uses in contexts with limited resources. “Technical novelty, Market novelty, refers to market, rather than product or service” (Zeschky et al., 2014). They confused FD and its effects.

Table 3.1 FD definitions with attribute conflation challenge

Author, year	FD definition
Lastovicka,1999	The degree to which customers' capacity to get and innovatively employ economic goods and services to achieve long-term goals is limited.
Paninchukunnath, 2013).	It is a zero-based method to resolve customers’ problems by offering very affordable, sustainable, and simple solutions, resulting in fast adoption by the customers.
Brem, and Iven, 2013.	Refers to products with incredibly large cost advantages over alternatives. They often lack complex technological features but still fulfill the most basic requirements at a reasonable cost with great value for the consumer.
Zeschky et al., 2014	It is not re-engineered solutions; they're goods or services made for extremely narrow uses in contexts with limited resources. 1)Technical novelty, 2) Market novelty, 3) Refers to market rather than product or service.
Cunha,2014	Product innovation is considered product innovation if there are few affluent consumers. In contrast, it is bricolage innovation when material resources are in short supply and improvisation when time is limited.

Wohlfart et. Al, 2016	It limits products and services to essential functions and integrates them into business models to make things affordable to cost-conscious consumers.
Levänen et al., 2014	It describes solutions developed in the context of limited resources. It is encouraged by consumer demand and low-cost competition in emerging economies where companies create solutions for low-income and growing middle-income sectors.

Another key issue identified is conceptual stretching, which occurs when a concept is applied to contexts for which it was not originally intended. This involves the use of terminology that incorporates previously unnamed or loosely related features, while attempting to preserve consistency in the definition (Berglund and Souleimanov, 2020). Concepts are often applied well beyond their usual scope. Individual researchers can enrich an idea. However, failing to evaluate why we need new terminology and employing language without precision can make more of our ideas "essentially contested" than necessary (Bronson, 1971). Due to academics using diverse languages to research the same event, theoretical understanding in this field will not grow. When expanded, the idea implies all and nothing (Collier and Mahon, 1993). Because FD has become too trendy to be discussed, there are theoretical gaps and uncertainty in practice. The transition process is illustrated by FD, which uses fewer resources to make accessible items. An individual, an organization, a network, a society, and even the planet are affected. 'Frugal design attempts to alter and adapt goods to foreign, emerging markets and establish R&D capability and product development centers. "Frugal design aims to alter and adapt goods to foreign, emerging markets and construct R&D capacity and product development centers" (Horn and Brem, 2013). However, developing FD by adapting goods to international and growing markets and creating R&D capacity and product development centers is stretching it. The sentence mixes two things. "It has a low to medium sophistication and a medium level of emerging market orientation and sustainability" (Brem and Wolfram, 2014). "It is not only necessary to accomplish more with less but also to do better with less. "It involves creating valuable goods and services that incorporate four primary traits that Western consumers highly value: quality, affordability, sustainability, and simplicity (Radjou and Prabhu, 2014). Other examples would broaden the idea by adding several characteristics to make it broadly feasible, such as high value, sustainability, and business model. This definition could be motivated by various factors, i.e., changing the emphasis of interpretation, the connotation of a buzzword, or the need for parsimony.

Table 3.2 Frugal Design definitions with concept stretching challenge

Author, year	**Definition**
(Tiwari and Herstatt, 2012).	It is the process of (re)designing goods and services in order to substantially lower costs while keeping user value in order to reach a wide number of consumers, especially individuals with low income.

George, 2012	It is a "low-cost, high-quality, and innovative goods and business model emerging in developing countries that are available for export to other developing nations and the developed world.
Agarwal and Brem, 2012	"Redesigning and developing products and processes from beginning to end up at the lowest possible cost while addressing regional needs."
Soni and Krishnan, 2014	Meeting the target goal using adequate, cost-effective means
Horn and Brem, 2013	Frugal design aims to alter and adapt goods to foreign, emerging markets and construct R&D capacity and product development centers.
Radjou and Prabhu, 2014	It is not only necessary to accomplish more with less, but also to do better with less. It involves creating valuable goods and services that incorporate four primary traits that Western consumers highly value: quality, affordability, sustainability, and simplicity.
Kuo, 2014	It is a product and service that concentrates on critical requirements while saving resources or removing unnecessary parts in the design process.
Sharma, and Iyer, 2012	It is simple and sustainably constructed, fulfills consumers' expected quality requirements while being created with significantly fewer resources, and consumes significantly fewer resources when used.

In addition to these two significant challenges, the research analyzed Suddaby's (2010) criteria and rejected inadequate definitions in Table 3.3, which hampered conceptual clarity. Few definitions pose conceptual clarity issues, but they assist us in grasping FD. Thus, they were left uncrossed. The first step yielded 67 definitions, 48 of which were retained.

Table 3.3 The definition of frugal design has a concept clarity challenge.

Authors, year	**Frugal Design Definition**	**Challenge: Concept Clarity**
Basu et al., 2013	It is "affordable, accessible, adaptable, and appropriate."	• Lack of parsimony • The conflation between attributes: It combines them without expressly discriminating between their respective meanings
Rao, 2013	FD is induced by scarcity, minimalist or reverse innovation, by economizing resource consumption	• Unclear terms: reverse innovation and minimalism • Uncertainty between the concept and its implications
Bound and Thornton, 2021	It is affordable, outperforms the alternative, and can be produced widely available.	• Unclear terms: outperform the alternative
Brem and Wolfram., 2014	It has a low to medium sophistication and a medium level of emerging market orientation and sustainability.	• Conceptual stretching to • Conflation between the concept and its result

3.3.2.2 Level Two: Semantic analysis

The second level of text analysis highlights FD definition semantics. Start with a qualitative content analysis employing semantic deconstruction and detailed definition review (Miller, 1951). Method for reducing words, morphemes, and clusters of words to primitives: The research used quantitative content analysis to better understand the interrelationship between crucial definition elements instead of looking at every word.

Step 3: Determine the definitional primitive

The research used grammatical analysis to analyze FD definitions. Adjectives and nouns are separated from verbs. The semantic function of each component within the provided FD definitions was subsequently examined. The primitives that describe the FD definition's overarching features were also explored. Explicit analytical guidelines were established, and each definition was evaluated independently. The results were subsequently compared to enhance the accuracy and reliability of the analytical process (Drisko and Maschi, 2016). The research uncovered six primitives of the FD definition: (1) nature: the inherent character of FD. 2) Scope: the magnitude of the modifications occurring across the target entity due to their nature, effects, and results. 3) Target entity: FD affects the analytical unit. 4) Means: the procedures the target entity uses to make the desired changes. 5) Outputs: FD impacts procedures, products, process modifications, and how an entity interacts with others, i.e., productivity, benefits, and efficiency. 6) Impact: long-term non-quantifiable impacts, such as value creation. The above six primitives, in our view, have sufficiently covered all facets in the definitions of FD.

3.3.2.3 Level three: Pragmatic analysis

The definitions analysis concluded with a pragmatic analysis. However, the First analysis helped us understand present definitions. This was one of the most challenging assignments. After all, it was required explicitly because it needed a systematic review and exhibiting the concept's definitional variability to define the goal and extension of a uniform FD definition. Gerring (1999) establishes eight conceptual quality criteria: familiarity, parsimony, resonance, coherence, differentiation, Field utility, depth, and theoretical usefulness (Gerring, 1999).

Step 4: Determine extensive and intensive

Gerring's criteria are strictly applied to this step's Final definitions. Gerring's first criterion is "familiarity," which measures a new term's clarity or intuition. “Parsimony,” the second conceptual requirement, concerns definition length. The formal definition of a concept should be concise. The third requirement, "Resonance," requires a memorable word that makes a cognitive click.

Table 3.3 shows that many FD definitions employ unclear parsimony. Most researchers still get cognitive clicks from FD, and most people may identify FD concepts that FD their daily lives. Therefore, FD meets these three conditions. Fourth is coherence, which is how well a concept's attributes (intention) and phenomena (extension) match. The Fifth criterion is how different a notion is from related concepts, instead of internal coherence. It defines the limits of concept extension. Significantly diverse concepts are easy to spot. Avoid the idea stretching problem addressed in this paper's second analysis phase by properly considering this variable. Being thrifty makes FD somewhat coherent. Due to its employment instead of other concepts, it fails to attain great separation. The sixth criterion, “Field utility,” assesses how concept creation may affect other semantic fields that academics explore. High-field utility notions do not decrease the conceptual value or the FD they are brought into. Seventh is “depth”. A profound concept has several related properties not required in its description. Concept utility depends on how many attributes it can group. The deep word FD embraces many occurrences. The depth of this idea is likely due to its undifferentiated nature, which allows it to take various phenomena from other areas. The Final criterion is “theoretical utility,” which describes the concept's role in theory development: Does it help create or improve new theories? FD has theoretical utility in multiple ways due to its widespread use in the literature.

Nevertheless, if FD is either an innovation process or philosophy, FD has limited Field utility because it blurs existing notions. Perhaps the FD is a mix of these. These components form an internal cohesive thought distinct from prior concepts and do not destroy it. It would also meet most criteria.

This means the broad concept merely meets Field utility. A distinct and consistent FD definition is needed to retain the broad conception's Field utility. FD Fits have several criteria: It feels familiar, is efficient in some situations, and is theoretically valuable. The FD concept gained popularity quickly, even if it may be unnecessary. In particular, differentiation issues can be devastating. Thus, such results illuminate implications while defining.

The research investigated word frequencies and Gerring's conceptualization theory to choose an appropriate extension for the primitives. The research examined FD's frugal and innovative features to define the world. “Frugal” problem-solving involves being careful and thrifty with money and food (Hossain et al., 2022). People frequently conflate design with any form of art and aesthetics, as the word “design” has grown overused and misunderstood. In etymology, however, design means “process or plan” of developing a solution that meets the community’s needs. A practical design must meet specific, measurable, achievable, and relevant criteria. As a result, better outputs are achieved. It will only earn the title if it significantly impacts the economic, social, and industrial levels and impacts many people (Bertero, 1996, June). A significant challenge is that defining FD necessitates separating it from related concepts. The research may overcome this issue by focusing on numerous peripheral attributes outside the core attribute. FD is described more thoroughly and distinguished from associated concepts by specific FD peripheral attributes important to its scope (i.e., a process with the expected outputs and influence). Despite trade-offs, we deliberately chose attributes that best expressed the concept. To properly understand FD, it must be distinguished from similar concepts.

We may also differ in FD regarding the scope of improvement and results. Different Fields have different ways of understanding progress. Through innovation, we expect incremental and radical improvements. Radical change requires a massive event, while incremental development entails gradual enhancements and process-oriented change (Norman and Verganti, 2014). Gradual improvement occurs through automation, simplifying, optimization, and redesigning instead of leaps and bounds. In contrast, FD focuses on strategic results. The entity for FD involves breaking frames and system components in various entities (such as an organization, an industry, and a society).

Following the nature of FD, the research defines FD as a resource-conscious innovation that systematically optimizes product inputs and maintenance/enhancement of outputs. Systematic optimization is essential for innovation.

3.3.3 Development: Frugal Design Definition

The research believes FD is a somewhat complicated term that should be used carefully. Understanding FD would help academics construct FD theory. Good conceptions are distinguished from bad ones by their goals, not vocabulary, characteristics, or phenomena (Lewis, 1970).

Table 3.4 Fugal Design Primitives containing (core and peripheral) defining attributes

Frugal Design Primitives	Core Attributes	Peripheral Highlighted attributes	Frequency Count
Nature	Resource consciousness		48
Scope	Products		21
Target Entity	Resources	Material	21
		Energy	16
		Information	13
		Space	9
		Time	7
Means	Systematic optimization		51
Output		Function	36
		Performance	32
		Inclusion	24
		Sustainability	34
Impact	Improved accessibility		38

Step 5: Ensure identified primitives

The research focused on screening the remaining definitions once more, delving deeply into each step qualitatively and verifying the primitives regarding the intention and extension of FD. Finally, according to word frequency, the core and peripheral defining attributes are identified, as shown in Table 3.4. Management, product, process, service, and social design research domains provide necessary and suitable conditions for finding FD examples. FD is a multidisciplinary field; thus, we should focus on existing knowledge rather than current trends.

Step 6: Define the FD concept

We constructed our definition based on the identified core attributes to redefine FD. We defined FD as “A resource-conscious innovation that systematically optimizes the product’s inputs (material, energy, information, space, and time) while rigorously maintaining or enhancing function, performance, inclusion, and sustainability.” As stated in step 4, FD uses core features with peripheral attributes to distinguish it from a low-cost design. It defines FD and its bounds. Carefully pick adjectives and nouns that balance semantics and parsimony.

3.4 Evaluation of the Frugal Design Definition

Evaluating a definition is crucial as it verifies accuracy, establishes reliability and validity, and identifies potential gaps we may have overlooked. Experts in the Field provide feedback on the presented results.

Step 7: Experts' feedback on definition

To collect feedback on our definition of FD, we invited 60 global experts, and 54 were accepted (response rate = 90%). The list of survey questions is in Appendix I. This group of 54 experts included 18 practitioners, 18 policymakers, and 18 researchers from academia and business. For definition, a one-way ANOVA test was used to compare average feedback scores among work area groups (Ross et al., 2017). Participants were divided by expertise into researchers, practitioners, and policymakers. When FD is Comprehensive, groups do not differ statistically. ($F(2,52) = 0.332402$, $p= 0.718741$), Complete ($F(2,52)= 0.041975$, p 0.958927). Applicable ($F(2,52) = 0.558685$, $p= 0.575421$), abstract ($F(2,52)=0.380191$, $p= 0.68565$), Consistent ($F(2,52)=0.158385$, $p= 0.85393$), and distinguishes FD from similar terms ($F(2,52)=0.13672$, $p= 0.872525$) We determined whether the definition of FD corresponded to the participant's understanding of FD in each of the three working area groups($F(2,52)=0.6$, $p= 0.552639$). This test shows that the proposed definition is precisely defined.

3.4.1 Final definition based on the survey feedback

Three categories can be made out of the responses we received from 54 participants: wording, criteria, and additional perspectives.

Experts recommend calling the concept "context-aware," "user-centric," and "adaptable." Those are necessary ingredients for successful FD. However, definitions should be abstract, and "resource-conscious" should be used to generate operational decisions on a case-by-case basis. Another debate concerns innovation and dramatic improvement. They do not feel that FD must introduce innovation. FD may always result in a "resource-conscious" improvement. The output must be described as "sustainable, performance, inclusion, and functional" to distinguish FD from related ideas. Attribute recognition, the most frequently highlighted in optimizing important entries such as materials, energy, information, space, and time, highlights the foundation of FD.

In contrast to traditional views that equate frameworks with cost reductions, experts argue that FDs should be driven by systematic optimization, which allows for targets and structured decisions. The scope is primarily product-oriented and reflects the tangible application of FD in design outputs. Output should consistently provide functionality, performance, inclusion, and sustainability, distinguishing between affordable innovation. Surprisingly, improving accessibility has an impact, expanding beyond users to a broader stakeholder ecosystem, including designers, managers, researchers, and partners. While some experts for parsimony conservation argue in their definition of FD, there is a consensus that there are important attributes such as resource efficiency capture to sacrifice integrity, such as affordable excellence, scalability, and resource efficiency capture. This brings FD beyond improvisation, focusing on value creation under restrictions while harmonizing justice, functionality, and sustainability.

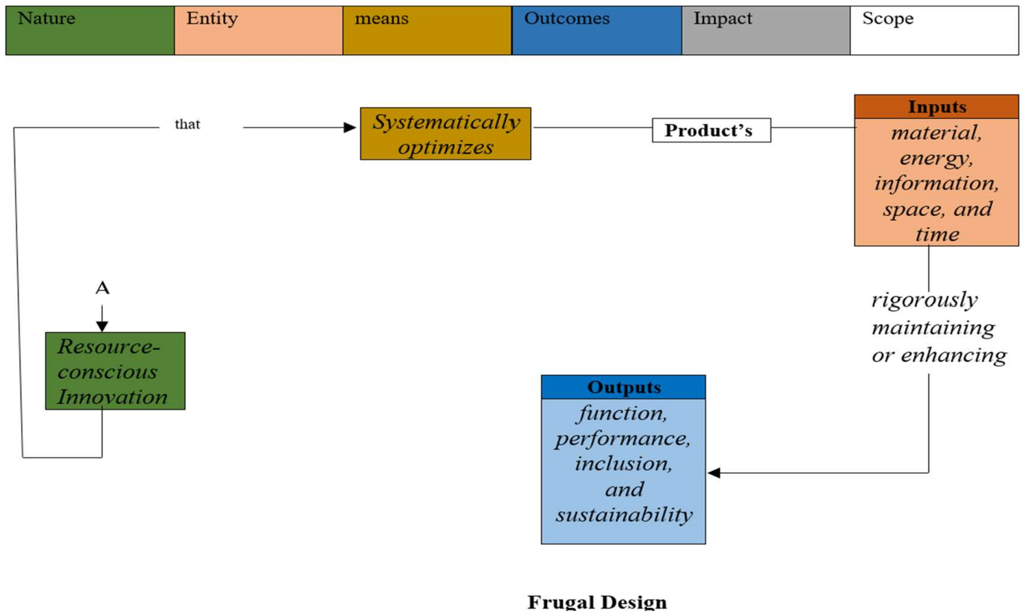


Fig. 3.3 Proposed Frugal Design Definition

FD is a socially formed notion based on various Fields of knowledge; hence, it has several distinguishing features. By considering each fundamental basic's most common defining qualities, we established six FD primitives: nature, scope, target entity, means, outputs, and impact, and finally, by logically linking them to define FD and thoroughly analyzing and distinguishing it from related phrases. The FD definition is. *"A resource-conscious innovation that systematically optimizes the product's inputs (material, energy, information, space, and time) while rigorously maintaining or enhancing function, performance, inclusion, and sustainability*."

The research demonstrated the importance of the FD definition's primitives and attributes using a simple conceptual model. Fig. 3.3 purposely incorporates FD-related categories of anticipated outputs to show the approach's FD building blocks and critical elements.

3.5 Discussion

Developing a precise and comprehensive definition of Frugal design can yield substantial Implications for the current research.

3.5.1 Theoretical Implication

- Collaboration and Communication Enhancements: Researchers, practitioners, and businesses can communicate more effectively regarding frugal design with a comprehensive definition. This may increase knowledge sharing and collaboration regarding developing and implementing frugal solutions.

- Identification and Assessment of Frugal Concepts: A clear framework helps identify frugal design concepts. This improves solution evaluation and minimizes confusion with "low-cost" options.
- Benchmarking and Scaling Up: A consistent definition helps compare frugal ideas across industries and contexts. Businesses can learn from one another and scale up effective frugal solutions for more significant effects.
- Strategic Analysis and Allocation of Resources: By understanding it, managers can incorporate frugal design into strategic planning and better focus resources on frugal solutions that meet specific demands and limits.
- Create a Frugal Design Culture: The clear concept encourages resourcefulness, creativity, and problem-solving with limited resources, which can improve workforce effectiveness and adaptability.

3.5.2 Practical Implications

Various case studies were performed to evaluate real-world examples of our approach. The cases in this part vary in maturity, allowing us to evaluate the suggested definition from many angles. Cases were collected using secondary data. Most preliminary data came from frugal entrepreneur observations, field visits, and surveys. Triangulation improves this research's credibility and dependability (Hussein, 2009). We meticulously investigated probable cases through videos, blogs, and media reports. We gained insight and critical information into each case by analyzing each case. We thoroughly investigated whether the cases could be categorized as frugal design. The National Innovation Foundation provided diverse financial, technological, and marketing support, crucial for identifying many cases in India. The following are the cases that explain the definition of frugal design.

Case 1: Embrace Infant Warmer

Embrace Infant Warmer illustrate a paradigm of resource-conscious innovation by systematically minimizing materials (phase change bags), energy (electricity, reusable), information (simple instructions), space (portable and compact), and time (persistent heat). This resource-efficient approach provides important outputs. It effectively maintains infant fever (function), provides life-saving thermal regulation (performance), ensures rural clinic records without incubators, and promotes sustainability through reusability and durability. The ultimate impact is the critical accessibility of intrinsic neonatal care at low resources. It improves the survival rates and health outcomes of protection needs by overcoming the limitations of traditional resource-intensive technologies (Misra, 2013).

Case 2: GE, ECG 400 Machine

GE, ECG 400 Machine embodies resource recognition using miniature components (materials), off-grid mode (energy) battery power, simplified user interface (information), compact and portable design (space), and fast diagnostics (time) achieved through systematic cost reduction through reduced design. This resource creation approach offers a critical cost. It provides essential diagnostic capabilities with accurate ECG measurements (performance), includes non-specialized users in remote locations, and promotes sustainability through its permanent and repairable nature. The effects are greatly expanded to access critical cardiac supply access in underserved regions, overcoming barriers to cost, complexity, and infrastructure limitations (Saikia et al., 2020 July)

Case 3: Jaipur foot

Jaipur Foot (India) embodies resource recognition through its dependence on rubber and wood (materials) that do not require external power (energy). This resource approach offers a critical cost: mobility (feature) is effectively restored. This makes it suitable for rural areas for guaranteeing durability (power) included in free cutting at low income and promotes sustainability through repairable and durable properties. The more profound effects are restoring work accessibility, mobility, and, more than anything, the dignity of those who are otherwise significantly disadvantaged (Arya and Klenerman, 2008).

The proposed FD definition contributes in two ways. First, it allows researchers to construct a consistent research stream by reviewing previous research. This method determines FD element interactions. However, it clearly describes how to build an FD and its permissive attributes for practitioners. Our findings highlight the need for a rigorous theoretical framework for FD and an extensive assessment of present definitions. In the present case, our systematic approach revealed and validated FI's important attributes from numerous definitions. The research ensured that only the essential qualities remained at each level of the definition's growth and that the final definition met many conceptualization researchers' quality standards. Finding FI's essential attributes helps explain its ambiguity and complexity. FD promotes openness to new fields of research and links knowledge disciplines with shared interests. As a resource-conscious innovation, FD systematically optimizes the inputs while rigorously maintaining/enhancing the outputs.

3.6 Summary

This chapter aims to provide a clear, consistent definition of Frugal Design (FD) to address the ambiguity and inconsistency. This definition can improve academic and practical understanding of FD. The proposed definition accomplishes two goals: it gives practitioners specific recommendations on applying FD and its essential attributes and gives researchers a solid base to construct a cohesive body of knowledge by reviewing existing literature. The chapter highlights the need for a solid theoretical foundation for FD and an extensive assessment of existing definitions. The research clarifies the intrinsic complexity of FD and its capacity to promote innovation in various industries by cutting costs and reevaluating value propositions. The chapter's goal is to set the framework for developing FD maturity models, taxonomies, and operational definitions, allowing for future investigation and application of FD across multiple disciplines.

Chapter 4

Frugal Design: Key Attributes and Outcomes

"Product attributes are the ingredients necessary for performing the product or service function sought by consumers."- Philip Kotler.

The current frugal approaches, focused only on developing countries and lower socioeconomic communities, overlook the generation of products for a diverse set of users. In order to get out of this narrow bias and develop more inclusive products, there is a need to identify the key attributes of frugal design. This chapter identifies essential attributes of frugal design with the help of Principal Component Analysis (PCA), Content Validity Analysis, and Word Frequency Count. This chapter presents the framework developed as part of the work, where four key attributes of frugal design, i.e., sustainability, functional, inclusion, and performance, are identified. The framework also underlines the importance of making the products more frugal for a wider society, including developed and developing countries, and all socioeconomic classes. The identified elements were validated with the help of the Delphi method in the form of design experimentation.

4.1 Introduction

According to the United Nations Organization (UNO), there are approximately 8 billion people on the planet, of which 648 million people in emerging nations are exposed to acute poverty and struggle for livelihood (UNDESA, 2022). This population is expected to rise to 9.7 billion by 2050 (UNDESA, 2022). This extremely rapid population growth will undoubtedly lead to many problems related to the overconsumption of resources and a decline in the quality of living. As the demand for resources continues to rise, so will energy consumption, resulting in environmental challenges, i.e., biodiversity loss and climate change. Also, the long-term availability of resources required to maintain the expanding population may become a concern (Xing et al., 2019). Expanding global markets will raise the costs of essential resources and inaccessible products, causing social stratification, inequality, and an unsafe living environment (Ding, 2003).

Various solutions, such as the 20R doctrine, circular economy, shared economy, etc., have been developed to tackle the above burning issues. However, none of them appear to be effective in solving them (Vasanth et al., 2012). Frugal Design is a comparatively new approach that gained significant growth in an era of scarce resources (Soni and Krishnan, 2014). It is a concept that emerges regardless of financial, technological, human, and other resource constraints. It produces economic outcomes catering to the marginalized society's fundamental needs (Roiland, 2016). The most notable examples of the Frugal Design are Selco: solar energy; in India, solar energy is provided to people at the bottom of the social and economic pyramid; Mitti cool, a refrigerator that runs without a battery; VodaPhone mobile: solar power mobile, M-Pesa, etc. (Horn and Brem, 2013).

Although frugal design has increasingly gained scholarly attention as an approach to developing affordable solutions, there is a gap in the literature regarding a comprehensive understanding of this approach (Upadhyay and Punekar, 2023). The literature has mainly concentrated on grassroots movements until now when describing this process (Brem et al., 2020). It is worth mentioning that frugal design may include attributes other than just low-cost innovation and the material constraints method. A specific requirement is to investigate and validate frugal design conception from a multi-attribute aspect. Earlier investigations, such as those of Rossetto et al. (2023), have highlighted dimensions of frugal design; however, their research on frugal design was primarily qualitative.

Therefore, the question remains: What attributes are required in the early design phase for creating the frugal design? The purpose of this research is to identify the attributes/outcomes of FD to give an appropriate response to this question. Based on the practical importance of frugal design and the discovered gaps in the literature about the attributes of frugal design, the current research tries to fill the gap by empirically conceptualizing frugal design.

The research significantly contributes to the existing reservoir of knowledge on frugal design. The research identified a consistent and valid multi-attribute of frugal design. The present research uses a mixed-method approach with multiple stages and a variety of methodologies to investigate and validate the assessment of frugal design. Finally, defining the attributes can help designers and engineers develop or enhance their frugal design process at an early stage of design to benefit from frugality-based advantages.

4.2 Process for identification of Frugal Design attributes

A mixed-method approach to construct a reliable and accurate scale to assess frugal design in the industry and companies, following the scale development process (Churchill, 1979). A three-stage research method with different studies included in each stage is shown in Fig. 4.1.

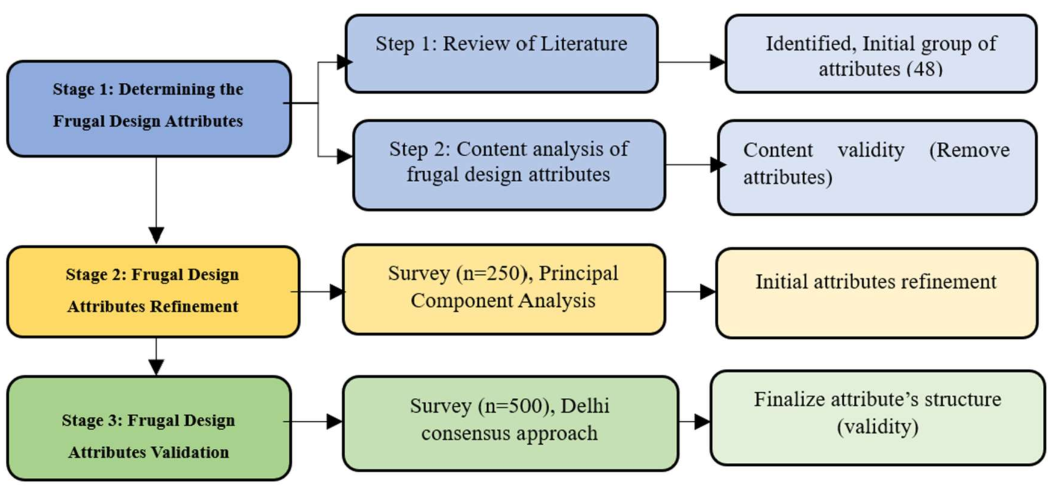


Fig. 4.1 Process for identification of Frugal Design attribution

In stage 1, a preliminary group of measuring attributes of frugal design was identified. The research at this stage integrated inclusion and exclusion criteria (Patinoand and Ferreira, 2018). A critical analysis of the literature on frugal design, in general, served as the foundation for the deductive method. Consequently, frugal attributes were discovered, and their indicators were selected depending on an adequate definition of the conceptual areas (Tesic et al., 2021). These indicators were derived from scales already existing in the literature. Furthermore, at this stage, inductive methods were used on qualitative data derived from a frugal design expert group assessment, preliminary analysis, and content analysis; in stage 2, the attributes were refined by utilizing reliability testing and principal component analysis (PCA) and the quantitative survey. In stage 3, the attributes were verified using a Delphi consensus approach in an expanded quantitative survey.

4.2.1 Stage 1: Determining the frugal design attributes

Step 1: Review of Literature

The research conducts a systematic literature review, which covers several studies done in the past. The literature was analyzed according to methodologies, trending topics, and industrial and geographical contexts. The initial outcomes from searching for "Frugal Innovation," "Frugal Design," and "Frugality" in the database, a total of 511 articles were retrieved, i.e., ABI/INFORM Complete 63, Emeralds 49, EBSCO 32, IEEE Explore 15, Inder Sciences 2, Scopus 44, Science Direct 99, Sage Premier 30, Taylor and Francis 70, Web of Science 63, and Wiley 44. The research focused on peer-reviewed publications to achieve the frugal design definition and higher levels of quality control. The article searches were limited to 2000-2023 because 2000 was the first year the term frugal design was introduced in the literature. The chosen articles were written in English to prevent erroneous interpretations based on the inclusion and exclusion criteria. 149 duplicate articles from well-known databases were eliminated throughout the search process. Furthermore, 43 out of 362 remaining articles were removed because they were outside our assessment's scope. A total of 319 articles have been found in the literature. Finally, 215 articles were used for the research.

The word-counting software, Sobolsoft https://www.sobolsoft.com, was utilized to calculate word frequency. For each attribute, the article-specific frequency percentage was computed. This task was carried out in the following parts.

1. A total 4,02,776 no of words were extracted from all the published articles related to design.
2. A list of the 1,294 most commonly used attributes related to design was selected.
3. To condense the database cluster, remove the attributes that are not directly related to the design. The attributes not belonging to the product feature or specification were excluded (e.g., potential, perspective, validate). Similar attributes were eliminated, and those whose word frequency was less than five were eliminated. Finally, the forty-eight attributes were generated to develop the initial list of Frugal Design attributes, as shown in Table 4.1.

Table 4.1 List of most frequently used attributes of Frugal Design

Word	Frequency	Frequency %
Sustainability	1305	24.4
Affordability	611	11.42

Functional	358	6.69
Inclusive	305	5.7
Simple	261	4.88
Accessibility	385	7.2
Availability	135	2.52
Performance	155	2.89
Quality	215	4.02
Aesthetics	109	2.03
Usability	132	2.46
Value	191	3.57
scalable	280	5.23
Environmental	118	2.2
Low-cost	74	1.38
Ability	71	1.32
Growing	69	1.29
Socioeconomic	67	1.25
Recyclability	62	1.15
Diverse	57	1.06
Robustness	42	0.78
Eco-friendly	36	0.67
user-centered	26	0.48
Viability	18	0.33
Portability	23	0.43
People-Centered	21	0.39
Durability	17	0.31
Effective	17	0.31
Scalable	23	0.43
Applicability	14	0.26
Resource efficient	11	0.2
Stability	11	0.2
Agility	19	0.35
Equity	8	0.14
Flexibility	8	0.14
Safe	9	0.16
Ergonomic	8	0.14
Ruggedization	8	0.14
Reproducibility	7	0.13
Reusability	7	0.13
Standardization	8	0.14

Socioecological	8	0.14
Manufacturability	8	0.14
Marginalized	5	0.09
Disruptive	7	0.13
Socially	5	0.09
Energy efficient	6	0.11
Desirability	7	0.13

Step 2: Content analysis of frugal design attributes

The content validity analysis method was carried out to validate the above attributes of Frugal Design (Yaghmaie, 2003). This pretest was designed to find and eliminate any unclear or missing information. A group of ten experts (professors) with similar backgrounds (i.e., design) evaluated the attributes using a four-point Likert scale, where 1 and 4 represent not essential and highly essential, respectively—further calculated the Item-Content Validity Index (I-CVI) and Content Validity Ratio (CVR) using equation no 4.1.

$$CVR=\frac{Ne\text{-}N/2}{N/2} \qquad (4.1)$$

N denotes the overall number of experts, whereas N_e represents the number of experts considering each attribute essential.

Thirty-nine attributes were deemed relevant for frugal design as they had a high CVR (>0.62) and an I-CVI score (>0.8). Other attributes, i.e., manufacturing, marginalized, disruptive, socially, energy efficient, and Desirability, were removed as they had a low CVR (<0.62) and I-CVI score (<0.8), indicating that the majority of experts did not consider them relevant to frugal design (Lawshe, 1975) as shown in Fig. 4.2.

4.2.2 Stage 2: Frugal Design attributes refinement

This stage aims to refine the database of attributes identified from the previous steps. Customers from India carried out a questionnaire survey. Since it is a developing nation, there are institutional gaps, resource limitations, and many customers at the bottom of the pyramid (BOP). The researcher provided the participants with examples of frugal products before distributing the questionnaire (see Appendix II); participants were expected to understand the frugal design fully.

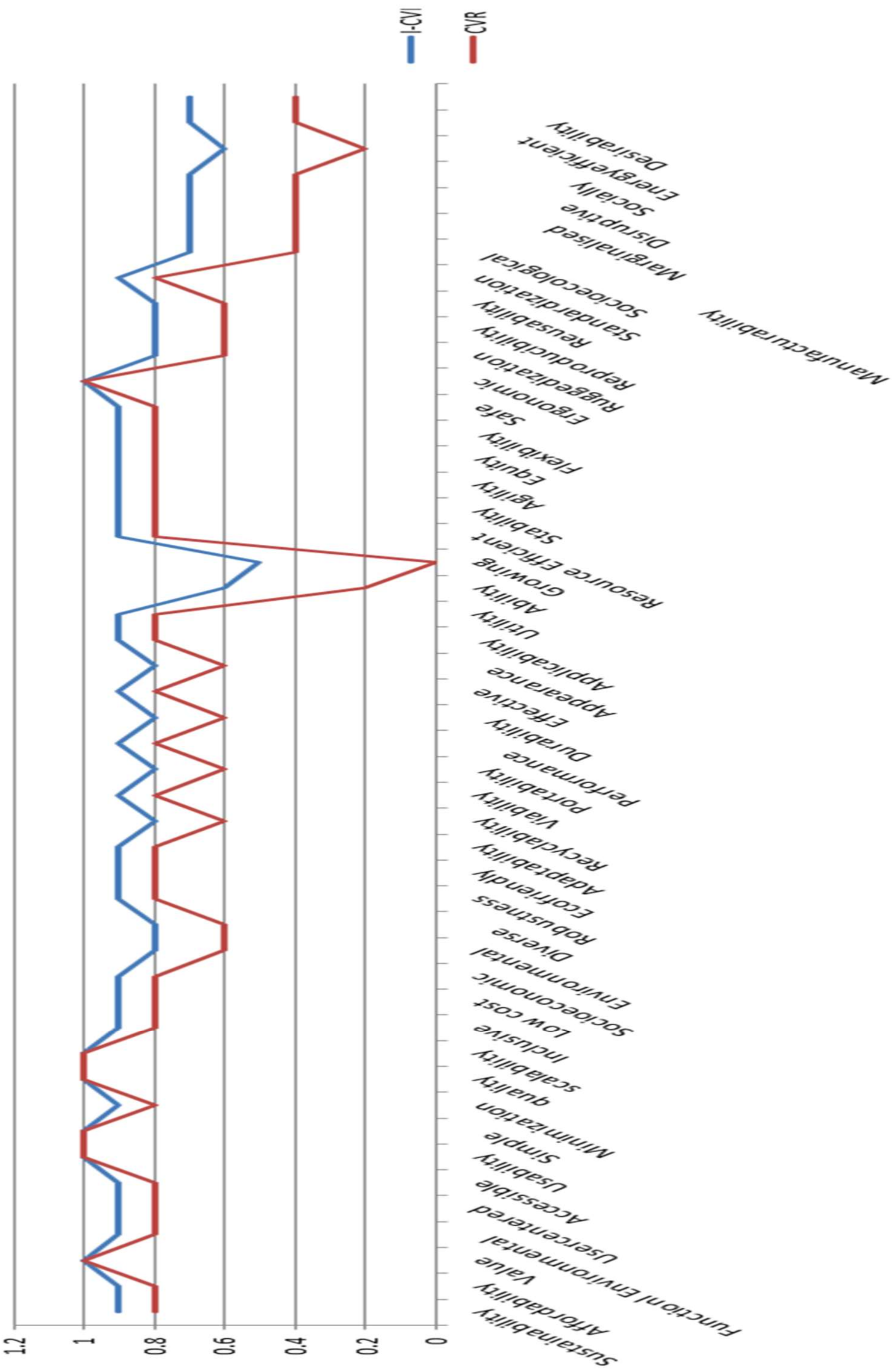


Fig. 4.2. Item Content Validity Index (I-CVI) and Content Validity Ratio (CVR) and of attributes.

The first part of the survey questionnaire was intended to gauge the participant's knowledge of the subject (Frugal Design). The opinions from participants were gathered in the next section using five-point Likert scales to identify the attributes of frugal design. Due to incomplete data and disengaged responses, 23 observations were dropped during data cleaning. In total, 250 participants constituted the sample for this research, achieving a valid response rate of 91.57%. We conducted a principal component analysis (PCA) on the set of 39 attributes to look at the attributes' structure and perform a preliminary evaluation of the validity and reliability of the attributes (Joshi et al., 2015). Further, the obtained attributes were standardized using equation no 4.2.

$$Z_i = \frac{X_i - X}{S} \qquad (4.2)$$

Where X and S are the Mean and Standard Deviation of the attribute, X_i and Z_i are the corresponding transformed attribute.

Principal Component Analysis (PCA) identifies the final list of Frugal Design attributes. PCA is a dimensional reduction technique that analyses the attributes' covariance and determines the critical attributes for characterizing the Frugal Design. It captures the maximum variation in data and transforms the existing dimension into a smaller space (Joliffe and Morgan,1992). Table 4.2 lists the attributes and their eigenvalues, arranged in decreasing order. Also, it indicates each attribute's strength (in percentage) when expressing the variation in data. From this, we can observe that twelve attributes obtained a cumulative strength of 100%. Sustainability is the most essential attribute as it provides the maximum strength, 20.821%, in capturing the variation in data.

Table 4.2 Eigenvalues of the selected attributes

Attributes	**Eigen value**	**% of Variance**	**Cumulative %**
Sustainability	8.375	20.821	20.821
Affordability	5.047	12.547	33.367
Functional	3.687	9.165	42.532
Inclusive	3.125	7.768	50.301
Simple	2.798	6.955	57.256
Accessible	2.274	5.654	62.911
Available	1.971	4.901	67.811
Performance	1.791	4.452	72.264
Quality	1.446	3.594	75.858
Aesthetics	1.392	3.461	79.318
Usability	1.245	3.096	82.414
Value	1.134	2.819	85.233
Scalable	0.945	2.35	87.584
Low-cost	0.79	1.965	89.549
Environmental	0.681	1.692	91.241
Diverse	0.565	1.405	92.646
Robustness	0.512	1.272	93.918
Ecofriendly	0.422	1.05	94.969
Adaptability	0.386	0.959	95.928

Recyclability	0.334	0.831	96.759
Viability	0.286	0.711	97.47
Portability	0.266	0.662	98.132
Use-centered	0.2	0.498	98.63
Durability	0.187	0.466	99.095
Effective	0.158	0.394	99.489
Appearance	0.086	0.214	99.703
Applicability	0.05	0.123	99.826
Socioeconomic	0.039	0.097	99.923
Resource Efficient	0.031	0.077	100
Stability	0	0	100
Agility	0	0	100
Equity	0	0	100
Flexibility	0	0	100
Safe	0	0	100
Ergonomic	0	0	100
Ruggedization	0	0	100
Reproducibility	0	0	100
Reusability	0	0	100
Standardization	0	0	100

The Scree Plot (Fig. 4.3) represented the results, as listed in Table 4.2, graphically. The eigenvalues are shown on the y-axis, and the attributes are on the horizontal x-axis. This graph considered the attributes up to the twelfth as eigenvalues of these attributes are higher than one as per Kaiser-Meyer-Olkin criteria (Kaiser and Rice, 1974).

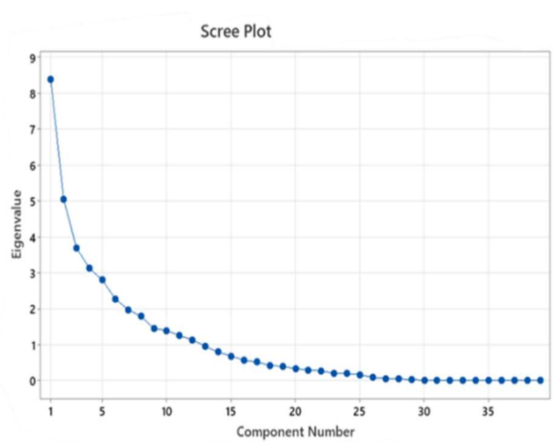


Fig. 4.3 Screen plot of Principal components and Eigenvalue

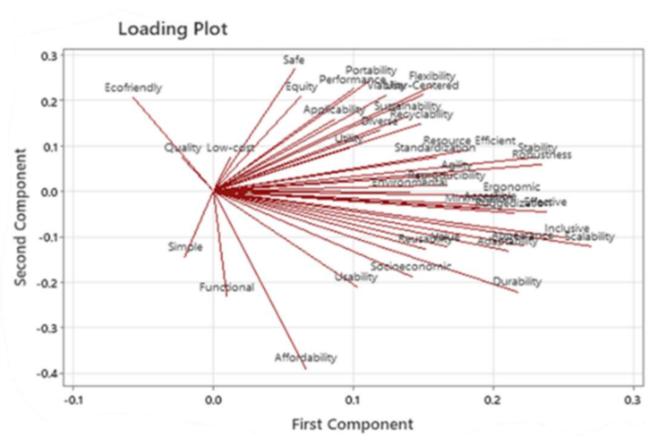


Fig. 4.4 Loading Plot of Highly Influenced Attributes

Loading plot helps to determine which attributes have the most significant influence on each other. Attributes loadings near -1 or 1 indicate a substantial impact on the component. The variable weakly influences the component if the loading is near 0, as shown in Fig. 4.4. According to this loading plot, the attributes Sustainability, Affordability, Functional, Inclusive, simple, accessible, available, performance, quality, aesthetics, and usability strongly influence and positively correlate, indicating that these attributes primarily contribute to Frugal Design.

The research identified the eleven attributes of frugal design (Sustainability, Affordability, Functional, Inclusive, simple, accessible, available, performance, quality, aesthetics, and usability. These attributes work together to develop accurate, frugal designs accessible to a wide range of people.

4.2.3 Stage 3: Frugal Design attributes validation

This research aimed to validate the attributes developed in the previous stage objectively. To prevent any discrepancies from outside effects, the refined scale is proposed to be re-evaluated with data gathered from a new sample in the final stage of the multi-attributes scale development process (Farooq, 2017). As a result, we specifically chose various samples during both stages.

Furthermore, the Delphi consensus approach was used in three rounds to test the frugal design features on customers in five Brazilian cities (Giannarou and Zervas, 2014). In the first round of the Delphi process, the criteria were first evaluated by being marked as either "important" or "not important." A 5-point Likert-type scale (5 = highly important to 1 = not important) was used in Delphi round two to rate the attribute's importance. In the final round, the Delphi process validated the frugal design attribute's importance level using a 5-point Likert-type scale. The research obtained 500 valid responses at the end of the data collection.

Table 4.3 shows the results of the Delphi consensus approach; some participants in the first round of the Delphi approach examined some attributes of the frugal design scale as not important; Nevertheless, the majority of the participants believed that all of the improved attributes needed to be included in the validation process in Delphi Round 2 to determine the degree of relevance and affirm the level of importance in the final round of the Delphi approach. Sustainability was rated critical by 480 participants (96%). Comparable to 495 participants (99%) thought the affordability attribute was necessary, etc. All of the attributes that participants deemed to be "important" fulfilled the consensus principles ($\bar{x} > 3$ and consensus rate > 75%), according to the Delphi consensus results. According to the Delphi consensus results, all the criteria assessed as "important" by participants have met the consensus principles (mean value > 3 and consensus rate > 75%) (Habibi et al.,2014). As a result, the Delphi consensus technique produced eleven legitimate attributes: sustainability, affordability, inclusive, functionality, usability, simplicity, quality, performance, and aesthetics.

Table 4.3: Frugal design attributes validation by Delphi consensus approach.

Validated Attributes	**Delphi round one**		**Delphi round two**		**Delphi round three**		**Delphi Consensus**	
	N	**%**	$\bar{X}$	σ	$\bar{X}$	σ	**%**	**C**

Sustainability	480	96	4.05	0.442	4.36	0.48	96.65	✓
Affordability	495	99	4.14	0.436	4.414	0.493	100.00	✓
Inclusive	415	83	3.34	0.456	4.120	0.32	91.30	✓
Functional	495	99	4.14	0.435	4.413	0.493	100.00	✓
Simple	470	94	3.91	0.91	4.23	0.5079	95.65	✓
Performance	390	78	3.28	0.58	3.6092	0.4884	94.33	✓
Usability	385	77	3.26	0.55	4.120	0.3255	86.96	✓
Accessible	465	93	3.91	0.91	3.9879	0.765	93.65	✓
Quality	390	78	3.28	0.58	3.6092	0.4884	94.33	✓
Available	410	82	3.33	0.79	4.082	0.321	86.83	✓
Aesthetics	430	86	3.49	1.24	4.36	0.48	96.65	✓
Value	300	60						

4.3 Frugal Design Attributes/Outcomes

A group of experts from academia and industry was used in the last step, which involved participants organizing and synthesizing the previously achieved eleven attributes in similar themes and patterns. After that, the attributes are categorized and sorted into clusters or themes. Each cluster is assigned a name that identifies as a final frugal design attribute. A set of measurable and specific attributes is created by refining the categories. Finally, the attributes are evaluated and prioritized regarding feasibility, importance, and impact (see Table 4.4) (Hoeppner and Scharf, 2004).

Table 4.4 Frugal Design Attributes

Sustainability	**Functional**	**Inclusion**	**Performance**
	Aesthetics	Accessibility	Quality
	Simple	Usability	
		Availability	
		Affordability	

Sustainability: the ability of a product to reduce its environmental impact throughout its lifecycle, from manufacturing to disposal, by employing eco-friendly materials, conserving energy, decreasing waste, and boosting recyclability or biodegradability.

- To provide effective solutions with fewer resources (Material, Energy, Information, Time, and space).

- To reduce the carbon footprint and ensure sustainable consumption with minimum energy

Functional: The product's ability to efficiently execute its intended function or tasks. It encapsulates the core features and capabilities required for the product to meet user needs and provide the intended results.

- Simple: Easy to understand, perform or use. Uncomplex.
- Aesthetic is a beauty, taste, and sensory experience associated with art and design.

Inclusion: products that remove financial and social barriers to ensure fair access and participation for everyone, regardless of their social, economic, or demographic backgrounds. This fosters a sense of community and makes goods affordable and accessible to various groups, including low-income and marginalized populations.

- Accessibility: products usable by persons with various abilities, limitations, and traits. It guarantees that products are accessible to everyone, including individuals with physical, sensory, cognitive, or other disabilities.
- Availability: how easily a product may be obtained or accessible by users. This includes product distribution, supply chain efficiency, and price, ensuring the product is accessible to its target market.
- Usability: the usability and learnability of a product. It concerns how easily a product can be controlled and how effectively users can achieve their goals.
- Affordability**:** To deliver Design processes and solutions that use low-cost materials, cost-effective distribution, economical production, and disposal.

Performance: the product's general effectiveness, stability, and responsiveness as well as its capacity to fulfill its intended function under particular circumstances.

- Quality: The extent to which a product meets stated standards or expectations regarding performance and longevity.

4.4 Summary

This chapter explores the growing concept of frugal design, emphasizing how it may provide practical solutions to modern problems. It highlights how challenging it is to define and conceptualize frugal design empirically and offers a paradigm built around four essential attributes: inclusivity, performance, sustainability, and functionality. These attributes serve as outputs of frugal products and also ensure resource conservation throughout their lifetime. Frugal Design gives a tremendous opportunity for future innovation by encouraging the development of affordable products that consume fewer resources while improving physical and social well-being. can enhance the impact and advantages of Frugal Design in the future.

Chapter 5

Frugal Design Evaluation Model

" Evaluation helps in understanding the direction and effectiveness of a concept, ensuring that it aligns with the intended goals."- Ralph W. Tayler.

Frugal design evolved as an essential approach for developing innovative solutions for resource-constrained areas. However, these designs have not been extensively examined for their effectiveness in achieving the desired frugal design outcomes. The research proposes a Frugal Design Evaluation Model (FDEM) to assess the efficacy of frugal products. The model is based on existing literature on frugal design and identifies the key criteria for being frugal in the last chapter (i.e., Sustainability, Functional, Inclusion, and Performance). Further, the user experience of (n=200 users) is also incorporated into the model to provide valuable and relevant insight. The proposed model is used to analyze the frugality of the design, and the current non-frugal products can be improved by incorporating the criteria that the designer neglected.

5.1 Introduction

In the modern world of change, where resource restrictions, inclusive growth, and technological considerations are crucial, frugal product design has evolved as a practical approach to delivering value for both users and enterprises (Le Bas, 2016) (Leliveld and Knorringa,2018). Frugal design addresses marginalized markets and promotes inclusive innovation by emphasizing resource efficiency, functionality, and affordability (Shahid et al., 2023). The level of frugality is heavily influenced by products that prioritize Sustainability and core functions, increase inclusion drastically, and maintain optimal performance throughout their lifespan (Kumari et al., 2023).

Initially, research on frugal product development emphasized cost reduction more than sustainability, including optimal performance and functionality. Since then, an extensive range of frameworks, i.e., Cost innovation, Jugaad, and Gandhian innovation, has been established to guide the product design process (Lim and Fujimoto, 2019). Evaluating the effectiveness of frugal design remains challenging. Upadhyay and Punekar (2023) recently created a methodology for designing frugal products in marginalized contexts. Still, it primarily focused on frugality's low-cost factor (Upadhyay and Punekar, 2013). Rao (2019) emphasizes sustainability as an essential aspect of frugal design and emphasizes the need to establish an evaluation technique for existing frugal design to build durable and safe frugal products (Rao, 2019). Le Bas (2016) and other recent research have brought attention to the ambiguity and confusion around the term "frugality," where low-cost designs are frequently referred to as "frugal" without fully satisfying all four frugality criteria ((Le Bas, 2016). Similar to this, various researchers, like Hossain (2018), Dabic et al. (2022), and Hossain (2020), have added to the current misunderstanding and deceptive usage. Therefore, frugal design efficiency has typically been diminished (Tiwari et al., 2014). Current frugal design practice prioritizes particular low-cost features. Designers must consider all three frugality criteria (Sustainability, Functional, Inclusion, and Performance) while developing frugal products (Kumari et al., 2023).

There is a need to develop a model to assess the frugality of the products based on frugality criteria. This research contributes to advancing frugal design practices and promotes widespread adoption across sectors by establishing a standardized assessment model. This will aid in defining what "frugal design" is and distinguish between various similar approaches. An evaluation model for frugal design uses qualitative and quantitative user experience measures. Finally, the proposed conceptual model aims to serve as an invaluable instrument for designers, engineers, and researchers in designing frugal products.

5.2 Frugality Criteria

The importance of being frugal in design is becoming more widely acknowledged as a means of producing high-performing, functional, inclusive, and sustainable solutions (Kumari et al., 2023). The development of frugal solutions that satisfy the demands of various people while reducing their adverse effects on the environment is guided by the five frugality criteria: sustainability, functional, inclusion, and performance. Below is a thorough description of how each criterion relates to frugal design outputs. The following are the frugality criteria.

- **Sustainability:** This criterion highlights a design's longevity and ecological footprint. Reduced resource use, waste generation, and detrimental environmental effects are the goals of sustainable frugal design. Frugal design can help create a future with greater environmental responsibility by emphasizing sustainability. It can lessen climate change, stop the loss of natural resources, and support a circular economy (Scoones, 2007).
- **Functional:** This requirement verifies that a design successfully fulfills its intended function. Practicality, dependability, and the ability to meet user needs are essential elements of a frugal design. The foundation of any effective design is functionality. A frugal product must accomplish its intended tasks with minimal resources (Doucet et al., 2009).
- **Inclusion:** This criterion brings a design's affordability and accessibility into account. People with different backgrounds and skill levels should be able to use a frugal design. It ensures that frugal design helps a broad range of people, especially those who might be marginalized or disadvantaged and require inclusion (Graham and Slee, 2006). Frugal design can encourage social equity and lessen inequality by taking affordability and accessibility into account.
- **Performance:** The criterion assesses a design's efficacy and quality. Despite having fewer resources, a frugal design should produce acceptable performance levels. Performance criteria are essential for a frugal design to be viable and achieve consumer expectations. A well-made, low-cost product can perform better than a more costly one in some aspects, including effectiveness or durability (Sonnentag and Frese, 2002).

It has been noted that some of the frugal designs are insufficient to deliver holistic frugal products. Current Frugal design often prioritizes specific elements, such as minimizing cost, while it is essential. However, a "Holistic Frugal" product necessitates a comprehensive viewpoint considering sustainability, core functionality, inclusion, and optimal performance.

A “holistic frugal design” is exceptional in its primary function. It addresses the user's fundamental requirements without including superfluous features or intricacies. It provides sustainable and inclusive products. Functionality should not be sacrificed to achieve cost reduction. A genuinely frugal product provides an optimal performance consistent with its primary function and purposeful use. This does not necessarily entail the pursuit of the most exceptional performance. Instead, the objective is to achieve satisfactory performance at a particular cost.

This research identifies various limitations of frugal product design practice that make integrating a product with frugal design challenging. The following are the gaps found in the literature.

1) The first is a lack of a comprehensive approach: the current design often concentrates on specific aspects of frugality (cost reduction). Still, it ignores the broader picture, limiting its applicability in different contexts.
2) The other challenge is the subjective criteria used by current approaches to evaluate frugality, which neglect the user experience, resulting in prejudices and inconsistencies.

So, there is a need to develop a quantitative and qualitative evaluation model that follows all four frugality criteria and caters to the user experience.

5.3 Research Methodology

This research aims to develop a conceptual evaluation model for assessing the frugality of existing frugal designs. The research follows the following phases, as shown in Fig. 5.1

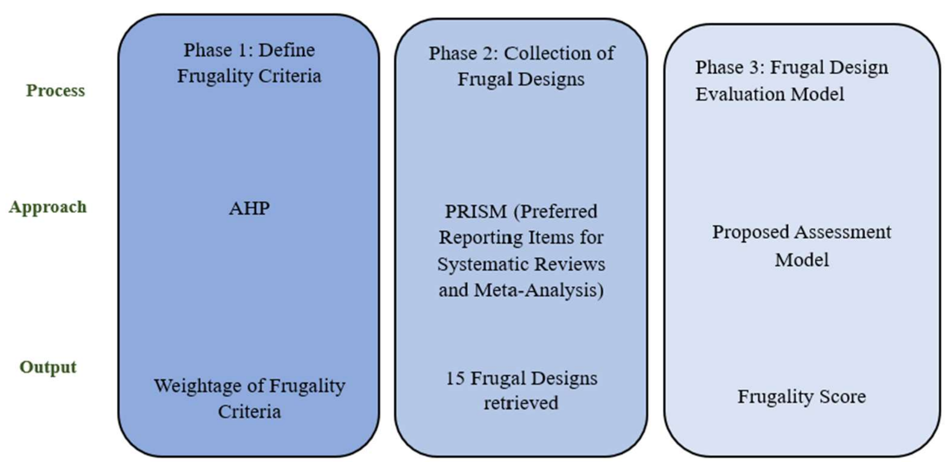


Fig. 5.1 Research Methodology

5.3.1 Phase 1: Define Frugality Criteria

The four frugality criteria (Sustainability, Inclusion, Functional, and Performance) derived by Kumari et al. (2023) were used for the evaluation model for frugal design. The emergence of these criteria has already been discussed in Chapter 4.

Importance of Frugality Criteria

To determine a framework's accurate and effective frugality score, the frugality assessment model assigns weights to each frugality criterion. The four criteria are ranked according to the weights assigned to them. The Analytical Hierarchy Process (AHP) provides the weightage for the frugality criteria. Pairwise comparisons are made at every level of the hierarchy by AHP to distinguish the importance of the criteria, and relative weights, also known as priorities, are calculated. AHP was first proposed by Saaty in 1980 (Wind and Saaty, 1980; Shahin et al., 2017).

The research comprises 15 highly skilled professionals, each possessing over two decades of expertise in their respective domains. The professionals have various backgrounds, encompassing Designers, Engineers, Policymakers, and Researchers. The participants were instructed to assess the significance of the criteria using a Likert scale (ranging from 1 to 9) through paired comparisons. The Engineers provide extensive technical and practical expertise, the Designers provide innovative and user-focused approaches, the Researchers contribute meticulous analytical and empirical observations, and the Policymakers offer strategic and regulatory perspectives. Their vast experience and diverse professional expertise provide a thorough assessment of the criteria. The normalized Eigenvector of the matrix results in the priority vector (PV), as shown in Table 5.1. The ratio of the random index (RI) to the consistency index (CI) is known as the consistency ratio (CR) see equations 5.1 and 5.2. Higher CR implies poor data quality. A CR value of less than 0.1 (10%) is generally desirable.

$$CR = \frac{CI}{RI} \quad (5.1)$$

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (5.2)$$

where λ_{max} denotes the matrix’s highest eigenvalue

Table 5.1: Pair-Wise Comparison of Frugality Criteria

	Sustainability	Affordability	Functional	Quality	Weighted Sum Value (WSV)	Criteria weights (PV)	Ratio=WSV/CW
Sustainability	0.25	0.25	0.25	0.25	1	0.25	4
Inclusion	0.25	0.25	0.25	0.25	1	0.25	4
Functional	0.25	0.25	0.25	0.25	1	0.25	4
Performance	0.25	0.25	0.25	0.25	1	0.25	4

Here, CR= 0, CR<< 0.01(Standard consistency ratio), the Matrix is consistent, and Frugality criteria priority was determined and weighted with the help of the AHP method. Table 5.2 indicates that the weight (%) of sustainability (25), Functional (25), Inclusion (25), and Performance (25), and that the consistency ratio (CR) is equal to 0, which means the matrix is perfectly consistent.

Table 5.2: Weightage of Frugality Criteria

Criteria	**Sustainability**	**Functional**	**Inclusion**	**Performance**
Weight (%)	25	25	25	25

5.3.2 Phase 2: Collection of frugal designs

The Web of Science (WoS), EBSCO, and Scopus databases were used to look for pertinent cases considered as frugal designs. The research adopted the following approach to reduce the risk of overlooking essential studies.

5.3.2.1 Frugal Design Case-studies Selection Process

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines divided the relevant frugal design case studies selection process into four stages (Moher et al., 2009). Finding and selecting appropriate cases was the first stage in the process. Each selected case is examined in the second and third stages to see if they are significant in addressing the research gap. Stage 1 provides a summary of the remaining cases.

Stage 1: Frugal Design Case-studies Identification and Screening

The search strings used the three databases in the first stage of the case search strategy. The strings were used to search the case research's titles, abstracts, and keywords. Ultimately, the research combined the outcomes from the three distinct databases and eliminated duplicates. One hundred twenty-eight case studies were found due to the initial search. Further, it is split into two parts.

- Initially, the research screened the previously identified 128 case studies. Case studies unrelated to frugal design or innovation were excluded through the title of the paper, its abstract, and its keywords. This contained articles that were returned by database queries but were manifestly irrelevant. In this case, 21 case studies were discarded, leaving 107 for further consideration.
- Furthermore, literature reviews, article references, and publication lists authored by the same authors were manually searched, as well as the case studies that cited these references. Finally, to find additional appropriate case studies, discussion via email or in person was conducted with the authors of specific promising papers. 36 more case studies were included as a result of this. Therefore, 143 articles were chosen for a thorough evaluation in the next stage.

Stage 2: Frugal Design Case Studies Eligibility Analysis

Inclusion criteria were used within the review (eligibility assessment). The following stage entails articles:

- Integrate frugal design and innovation into one modelling framework.

- Include frugality criteria (Sustainability, Functionality, Inclusion, and Performance).

Lastly, the research did not include reports whose outcomes have not been published for over ten years. By using this criterion, 59 articles were determined to be pertinent for the review and incorporated into the next stage.

The research tried to gather information regarding the implications of categorizing frugal design case studies and how products of frugal design frameworks impact the achievement of specific project objectives from the remaining 59 cases.

Stage 3: Frugal Design Case-studies Include process

The final stage (44 case studies) was selected. Out of these, 15 frugal design cases were chosen for analysis. A flowchart of the search and selection procedures is shown in Fig. 5.2, which adheres to the PRISMA recommendations (Moher et al., 2009).

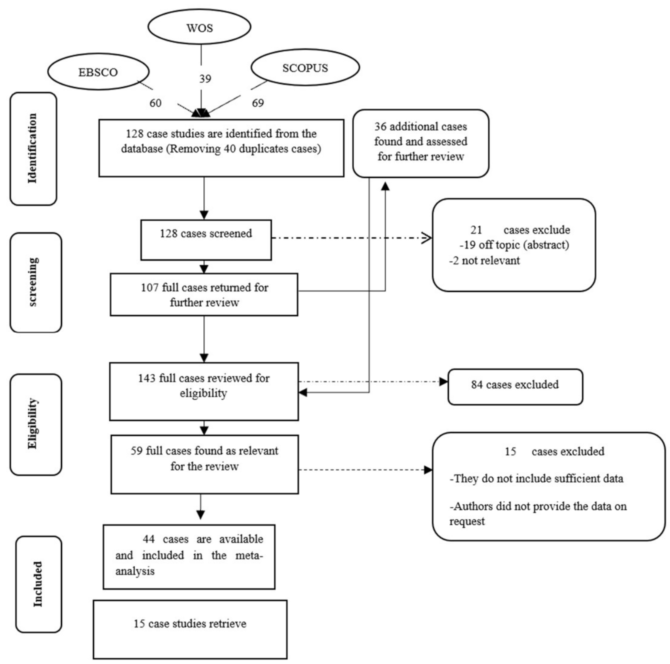


Fig. 5.2 PRISMA Methodology

5.3.3 Phase 3: Frugal Design Evaluation Model

The evaluation model for frugal product design is illustrated in Fig. 5.3. The following steps must be followed.

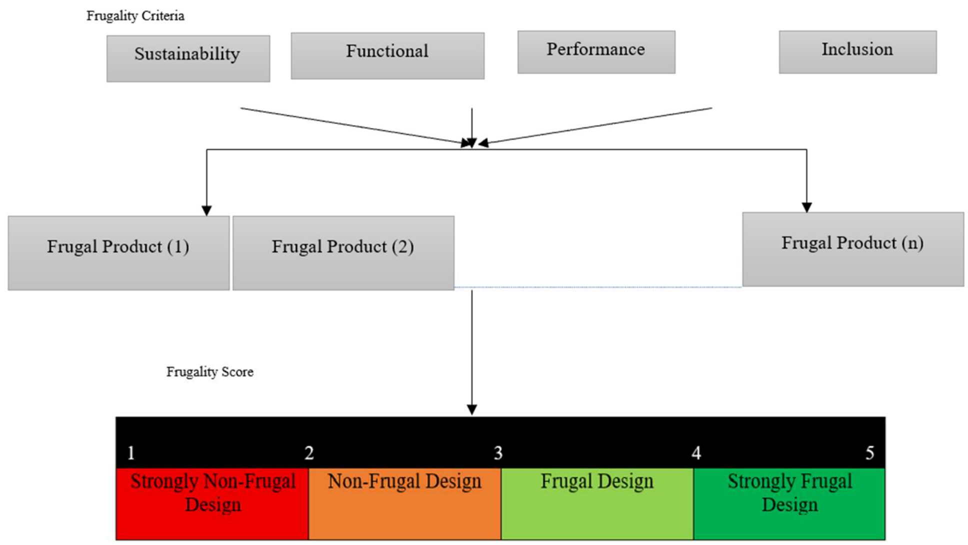


Fig. 5.3. Assessment model for frugal product design frameworks and products

Step 1: Choose a product for analysing frugality.

Step 2: Determine the frugality criterion for evaluating frugal design. Each criterion is prioritized based on its weight.

Step 3: Perform the Frugality Evaluation Test: The research assesses the effectiveness of frugal product design to meet specific frugality criteria (e.g., Sustainability, Inclusion, Functional, and Performance). For evaluation, the research used frugal products. The research employs a stratified sampling method for selecting participants (Singh et al., 1996). The research involves the participation of 150 users (10 real consumers of each of these product categories). The participants were asked to complete a survey with scenario-based questions (Riedmaier et al., 2020) and rate the frugal products based on their experience on a 5-point Likert scale.

Step 4: Once Likert-type surveys were used to gather data, the mean rating submitted by users was included within the proposed frugal formula (see equation 5.5).
For assessment of existing frugal design, we have created a matrix [A], based on the rates provided by the user groups using the Likert scale a matrix $[A]_{m*n}$ was generated. Where m is the number of rows and n is the number of columns.

$$[A]_{m*N} = \begin{vmatrix} \bar{X}_{11} & \bar{X}_{12} & \bar{X}_{1n} \\ \bar{X}_{21} & \bar{X}_{22} & \bar{X}_{23} \\ \bar{X}_{m1} & \bar{X}_{m2} & \bar{X}_{mn} \end{vmatrix} \qquad (5.3)$$

To compute the weighted average frugality score (W) of the user ratings, a matrix is created using Equation 4, with the weight of each frugality criterion multiplied by the corresponding rating in the matrix.

$$W = w_i \begin{vmatrix} \bar{X}_{11} & \bar{X}_{12} & \bar{X}_{1n} \\ \bar{X}_{21} & \bar{X}_{22} & \bar{X}_{23} \\ \bar{X}_{m1} & \bar{X}_{m2} & \bar{X}_{mn} \end{vmatrix} \tag{5.4}$$

The following is a general equation for calculating the frugality of Frugal product design

$$\text{Frugality Score} = \frac{\sum_{i=1}^{m} \sum_{j=1}^{n} w_i \bar{X}_{ij}}{\sum_{j=1}^{n} w_i} \tag{5.5}$$

Here, w_i is the weight applied to x values,

$\bar{X}_{ij}$ is the mean value of the user's rating,

Step 5: The research employs fuzzy logic to establish the categorization of the frugality score, which ranges from 1 to 5. Fuzzy logic is a potent methodology to manage subjective judgments and uncertainty in decision-making processes (Kosko and Isaka, 1993). Triangular membership functions were used to build fuzzy sets for the categories of frugality score "strongly frugal," "frugal," "non-frugal," and "strongly non-frugal." The delineations for these categories were determined by deliberation with a panel of 15 professionals used during (phase 1) Define Frugality Criteria, providing the Importance of Frugality Criteria, verifying that the classification standards are solid and well-informed. We can effectively account for the subjective nature of frugality assessment by utilizing fuzzy sets to evaluate a product's frugality score. These membership functions allow for evaluating the extent to which a specific frugality score (a)

belongs to each fuzzy set. The following fuzzy sets are utilized to define the frugal design into several frugality score categories:

- The designs with a frugality score range of (4 – 5) are categorized as "Strongly Frugal." These products achieve high Sustainability, Inclusion, Functional, and Performance scores, demonstrating excellence in all frugality criteria.

$$\text{Strongly frugal (a)} = \begin{Bmatrix} a-3, & 3 < a < 4 \\ 1, & a = 4 \\ 5-a, & 4 < a \leq 5 \\ 0, & otherwise \end{Bmatrix} \tag{5.6}$$

- The designs with a frugality score range of (4 - 3) are categorized as " Frugal." These products satisfy the frugality criteria by balancing cost, performance, and primary function.

$$\text{frugal (a)} = \begin{Bmatrix} x-2, & 2 < a < 3 \\ 1, & a = 3 \\ 4-a, & 3 < a < 4 \\ 0, & otherwise \end{Bmatrix} \tag{5.7}$$

- The designs with a frugality score range of (3 - 2) are categorized as "non-frugal," Products in this category exhibit some frugal characteristics but are generally not regarded as frugal.

$$\text{non} - \text{frugal (a)} = \begin{Bmatrix} a-1, & 1 < a < 2 \\ 1, & a = 2 \\ 3-x, & 2 < a < 3 \\ 0, & otherwise \end{Bmatrix} \quad (5.8)$$

- The designs with a frugality score range of (2 - 1) are categorized as " Strongly non-frugal," The lowest scores in this range indicate products that perform poorly on frugality criteria.

$$\text{Strongly non} - \text{ frugal (a)} = \begin{Bmatrix} 1, & if\ a = 1 \\ 2-a, & if\ 1 < a < 2 \\ 0, & otherwise \end{Bmatrix} \quad (5.9)$$

5.4 Evaluation of Frugal Design

The research found fifteen products for the assessment (see Fig. 5.2). The research involves the users of the previously selected products (step 2), which comprise the target participants for this evaluation. Furthermore, the authors employ a stratified sampling method to assign participants and further refine the sample based on two critical factors, Product Category, and Experience Level, to collect more focused data. Segment the target participants into strata according to the fifteen product categories (in step 2). This enables the collection of user experiences across a wide variety of products. Further, stratify inside each product category according to the length of the user experience. Only those who have utilized a selected product within that category for at least six months will be eligible to participate. This assures that participants have had sufficient time to establish well-informed opinions of the three frugality criteria (i.e., Sustainability, Inclusion, Functionality, and Performance). The research involves the participation of 150 users (10 real consumers of each of these product categories).

A survey instrument with scenario-based questions was developed for the research (see Appendix III). The survey employed a format with multiple modes. Both physical and online questionnaires were used to distribute scenario-based questions. Furthermore, the survey was provided in English and regional languages to increase user involvement and improve the accuracy of the data collected. In these questions, participants are asked to share their experience using the product on a 5-point Likert scale by rating the three frugality criteria in actual scenarios. The suggested formula was used after converting each response to a numerical number. Based on the rating provided by the users, a matrix $[A]_{m*N}$ was created. To produce the weighted average of frugal products, the matrix $[A]_{m*N}$ is further processed using equation (5.4), here w_i is multiplied with $[A]_{m*N}$matrix.

As mentioned in the methodology, Formula Equation 5.5 calculates the Frugality score. The corresponding frugality scores of frugal products obtained from this computation are shown in Table 5.3.

Table 5.3: Frugality Score of Frugal Product Design

Frugal Products	**Frugality Criteria**				**Frugality Score**
	Sustainability	**Inclusion**	**Functionality**	**Performance**	$\frac{\sum_{i=1}^{m}\sum_{j=1}^{n} w_i \bar{X}_{ij}}{\sum_{j=1}^{n} w_i}$ **Here, m (no of frugality criteria) =4 and n (no of frugal designs) =15**
	25	25	25	25	
Disposable Fast Fashion (Zudio)	1	1	2	3	1.75
Disposable Sanitary Pads(paree)	1	3	3	1	1.86
Tata nano	3	3	2	1	2.25
Husk Power System	3	3	3	4	3.25
Eco cooler	3	3	4	3	3.25
Plastic milk packaging	1	3	3	3	2.50
Plastic Toothbrush	1	3	3	3	2.50
Disposable razor (Gillette)	2	3	3	2	2.70
Furniture-Plastic chair(neelkamal)	2	3	4	4	3.30
Single-Use Paper Cutlery	1	2	2	2	1.62
Tata Swach	3	3	3	3	3.00
Jaipur leg	4	5	4	4	4.25
Embrace global, keeping newborns warm	4		3	4	3.57

Logitech-M215	2	3	3	3	2.71
Akash tablet	2	4	3	4	3.25

As shown in Fig. 5.4, the frugality scores for the fifteen products ranged between 1.75 to 4.25, respectively. This implies that the designs (single-use paper cutlery, Disposable Fast Fashion, and Disposable Sanitary Pads) are in the strongly non-frugal category as their frugality score lies between (1-2)(see equation 5.9).

Plastic Toothbrush, Logitech-M215, Plastic milk packaging, Disposable razor for them, the frugality score lies between (2 – 3) in the non-frugal category (see equation 5.8). As per the proposed evaluation model, data analysis showed that the designer neglected to include the four frugality criteria in their design development method, proving that these products do not adhere to frugality.

Designs (Tata nano, Eco-cooler, Furniture-Plastic chairs, Husk Power system, Tata swach, Jaipur leg, embrace global keeping newborns warms, and Akash tablet) with a score of (3 - 4) are considered in the frugal category (see equation 5.7); however, these designs have gaps because they do not sufficiently include the frugality criterion. It has been discovered that the Jaipur leg is strongly frugal since it considers all criteria that were overlooked in earlier design frameworks (see equation 5.6). The design of these products is substantially enhanced by the inclusion of these previously disregarded frugality criteria.

Conversely, the absence of these criteria in the products above leads to a lower frugality score. It represents significant inefficiencies and raised costs. These designs may incorporate specific cost-saving techniques; however, they must be sufficiently optimized, which may result in higher costs than are necessary. Complex designs and unfavorable cost-performance ratios often result from including components that do not improve the core functions. It is essential to Assess and redesign the frugal design by concentrating on eliminating superfluous features, enhancing inclusion, sustainability, and performance, and reducing costs. To address this in a frugal design, an evaluation process should focus on these issues. In this manner, it will be more efficient, improving its efficiency and achieving frugality benchmarks through the implementation of less costly materials and production systems that are more effective. Designers can use these measures to think about designing for frugality.

Fig. 5.4 Frugality score

5.5 Summary

This chapter provides engineers and designers with an evaluation methodology for frugal product design that enables them to rate the frugality of designs and provide recommendations for enhancement when a design fails to meet the required level of frugality. The model incorporates user requirements, which are critical in identifying areas for improvement and verifying that products meet frugal standards like performance, functionality, sustainability, and inclusivity. The three main stages of the process include establishing and ranking frugality standards, assessing designs according to user experience, and examining the outcomes to pinpoint areas that require improvement. Research on fifteen designs revealed why particular user groups choose some items while ignoring others, allowing designers to improve their evaluations. However, designs with lower scores are not always faulty; they may fail to meet all frugality criteria. This evaluation model is an effective tool for helping designers create frugal, high-quality designs.

Chapter 6

Uncovering the Barriers: The Root Causes of Frugal Design Failure

" To fix the problem, find the root cause"- Nir Eyal.

Frugal design, a strategic approach prioritizing sustainability, Functionality, performance, and inclusivity, has emerged as an effective tool for inclusive and accessible innovation. However, many firms struggle to properly execute frugality requirements during production, resulting in unsatisfactory outputs. This research performs a comprehensive product lifecycle analysis to uncover the underlying causes of frugal design failure. Using a closed-loop frugal product lifecycle modeling framework and several root cause analysis techniques, this research finds the inefficient use of essential input resources (materials, energy, information, space, and time) as a critical cause of failure. The findings emphasize the importance of a systematic approach to resource management and creating new design solutions to implement frugal design goals successfully.

6.1 Introduction

Frugal Design has emerged as a valuable approach to providing value to users and entrepreneurs in the current dynamic environment, where limited resources, inclusive development, and technology factors are critical (Le Bas, 2016); (Leliveld and Knorringa,2018). Frugal design prioritizes affordability, functionality, and resource efficiency to reach underserved markets and encourage inclusive innovation (Shahid et al., 2023). It has applications in many areas, such as healthcare, banking, transportation, housing, and education, where limited resources must be fully utilized to meet the needs of the underserved (Pisoni et al., 2018). It aims to close the accessibility gap by ensuring that even those living in less privileged communities can benefit and feel good about themselves (Agarwal and Brem, 2017).

Despite its benefits, many organizations fail to develop frugal designs as they do not fulfill the criteria in their entire lifecycle, identified in Chapter 4, with the help of the frugal design evaluation model. Limitations in frugal design are primarily in practice and theory (Cai et al., 2019). These limitations may include a lack of understanding of the need for optimal utilization of resources throughout the life cycle of a product that tends to be complex (Brem et al., 2020). To increase alignment with frugal design criteria, the root causes of non-compliance with these assessments must be identified. However, during a product's life cycle, from early design to production and delivery to the entire product, there could be hundreds of different causes for unintentional failure. It requires a deep understanding of the product life cycle, from raw material extraction to the end-of-life phase (Barnikol, 2024). Designers and manufacturers can successfully address concerns about divergence from frugality criteria by determining the particular causes that caused the variances and adopting targeted techniques.

As a result, analytical Root cause analysis (RCA) techniques based on closed loop modeling that combine product and process models with heterogeneous data from various product lifecycle phases must be developed to address the underlying reasons for frugal design failures. This research identifies the root causes of frugal design failure with the help of a closed-loop frugal product lifecycle modeling strategy.

6.2 Closed-loop frugal product lifecycle modeling

In a closed-loop model, two loops of self-resilient manufacturing systems existed: intra-loop and inter-loop. Inter-loops are based on information gathered during various product life cycle phases. In contrast, intra-loops are feedback loops that rely on information from the same and another phase of the product life cycle, as shown in Fig. 6.1.

6.2.1 Inter-loop of Frugal Product Lifecycle Modeling

The interloop across various phases of the product lifecycle (i.e., raw material sourcing, manufacturing, Transportation/Distribution, Installation, use, end of life) is vital in enhancing frugal design's diagnostic and optimization capabilities. This inter-loop expresses integrated feedback ideas at each level and allows knowledge to persist throughout the product, especially when dealing with uncertainty or failure. Each phase feeds essential information back into the system, aiding diagnosis (determining where and why the failure occurred in frugal design) and optimization (implementing immediate changes to reduce the impact of the failure). Defects can be detected early, allowing faster iterations without testing the entire frugal product. Through continuous information flow, the frugal product development process identifies and resolves faults at various phases in the product lifecycle rather than waiting for the product to become obsolete or degrade (Lemmens et al., 2007). In the event of a failure (where the cause is not immediately apparent), this integration allows for rapid determination of the root cause by analyzing data at different levels. An analytical analysis should be performed for the lifecycle from raw material to the end of life to identify the root causes of product failure at each life cycle stage (Shruti et al., 2013). Identifying root causes early and directly helps the designer's design decisions, reducing the need for redundant design refinements and testing.

6.2.2 Intra-loop of Frugal Product Lifecycle Modeling

In the manufacturing Phase of frugal products, the simulation process helps control various activities such as production planning, machine setup, assembly, testing, and inspection. At this phase, damaged or leftover products can be identified and returned to the raw material for reuse as secondary materials, ensuring that necessary resources are not discarded. Creating a way to improve this feedback process is essential to improving resource use and reducing waste. This method will involve determining the quality and characteristics of the faulty equipment and what reprocessing needs to be done, and this information should be incorporated into the new cycle.

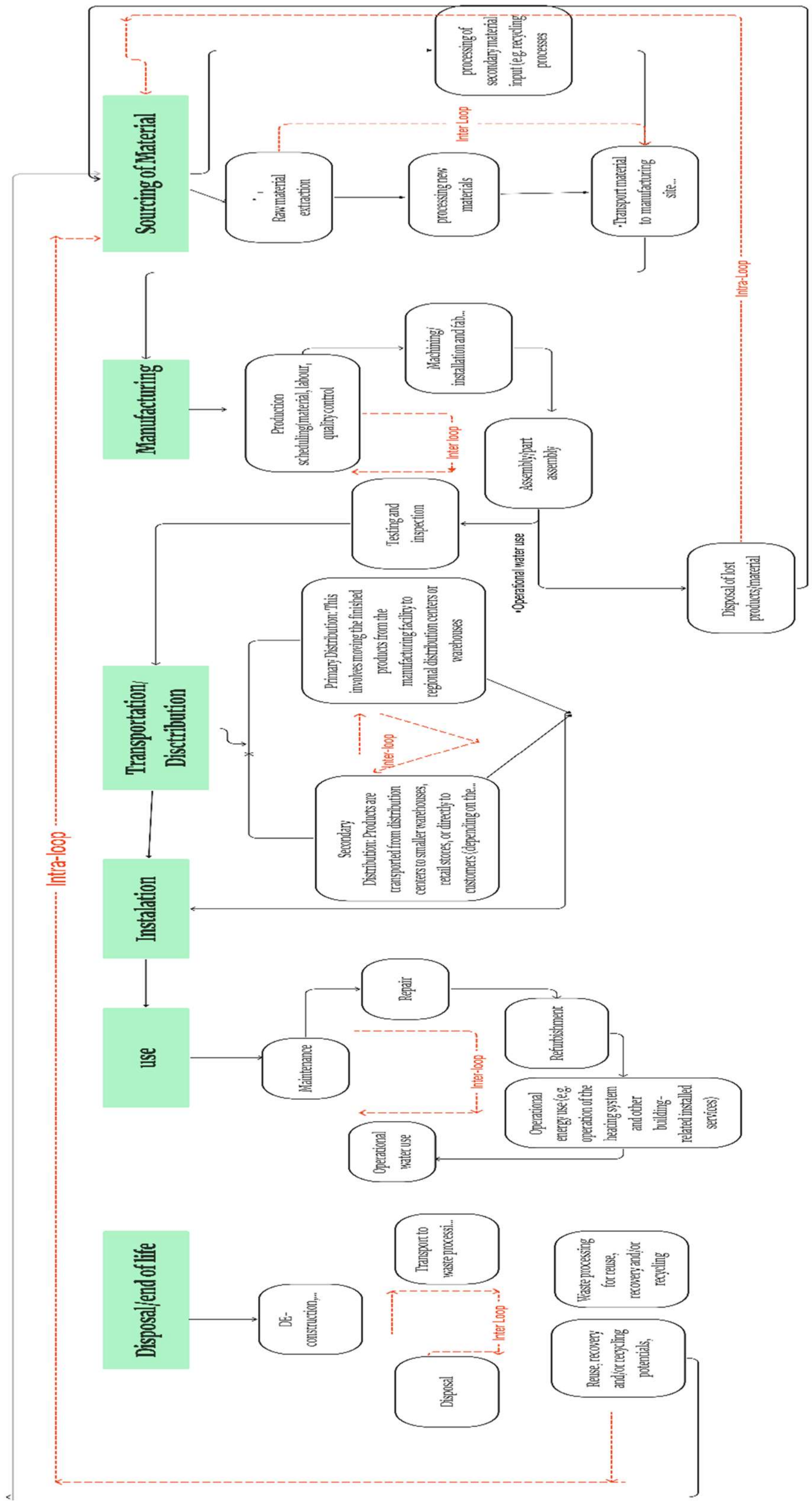


Fig. 6.1. Close loop frugal Product lifecycle strategy

The analysis will consider factors such as energy consumption, materials, and recycling costs to ensure that secondary materials maintain product quality and are based on the criteria of frugality.

6.3 Research Methodology

The research selected cases of non-frugal products, such as sanatory napkins (Paree) and fast fashion industries (Zudio), which were evaluated in the previous chapter. To identify and address the causes of these failures in these cases, the research uses the comprehensive (Root-Cause Analysis) method to identify and resolve these critical issues, allowing organizations to improve their design processes and relate to frugality criteria (Doggett,2005). As shown in Fig. 6.2, the following two-stage research method was adopted: 1) Scenario-based questionnaire survey, 2) Data Collection and result analysis

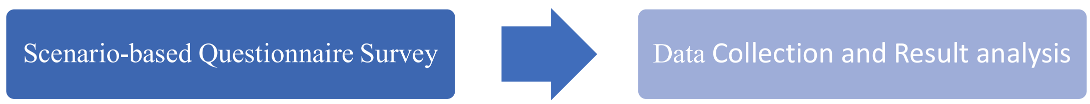


Fig. 6.2: Research Methodology

The research followed the methodology employed by Al-Zwainy (Al-Zwainy, 2013) to conduct the scenario-based questionnaire survey. A multidisciplinary team of thirty experts in engineering, manufacturing, construction, management, business, an d sustainability was formed. These experts are working professionals in the firms chosen as a case for the research to ensure they have knowledge and experience at every stage of the product's life cycle. According to this selection, they can offer knowledgeable insights into various lifecycle phases and circumstances. Compatibility and individual abilities are carefully considered when selecting team members. Collaborative problem-solving promotes positive team dynamics and requires excellent interpersonal and communication abilities. To produce frugal products, the cooperative approach fosters decision-making, broadens viewpoints, and improves problem-solving abilities (Pollastri et al., 2013).

6.4 Data Collection and Result Analysis

The research uses a scenario-based survey to determine the root causes. This method was chosen because it provides quick data. An exploratory research method was used to identify and analyze the root causes of the failure of existing frugal designs. Due to the specific nature of each company's data, it is not easy to collect data and information about frugal products throughout their life cycle. This approach facilitates personal contact with experts throughout the interloop and intra-loop frugal product lifecycle model, identifying the root causes of frugal design and non-compliance with frugality standards at each lifecycle phase (Riedmaier et al., 2020).

Determining the "sub-causes" and "main root causes" of the problem is critical. Only a complete understanding of the process and extensive experience with innovative tools and procedures could identify the root causes. Creative thinking strategies include fishbone diagrams, mind mapping, Pareto analysis, brainstorming, nominal group technique, metaphorical thinking, and why analysis helps to identify the root causes. The authors focus on the following techniques to perform the RCA (Suherman and Vidakovich, 2022).

Step 1: Ishikawa Diagram,

Step 2: Sub-cause prioritization

Step 3: Five Why Method

6.4.1 Step 1: Ishikawa Diagram method:

Professor Kaoru Ishikawa, a great management professor, introduced this Root cause-effect analysis method in the 1960s. Later, his work was documented in the 1990 book "An Introduction to Quality Control." The resulting diagram, often called the Ishikawa or fishbone diagram because of its skeleton, has become a widely accepted tool for understanding and analyzing complex problems. This approach provides a visual representation for investigating the root cause of complex problems (Wong et al., 2016).

The following steps were utilized to identify the possible reasons for this problem:

1) The scenario-based survey was conducted (see Appendix IV) with thirty experts to identify the main reasons for the failure of frugal products and the factors contributing to these differences. Each possesses over two decades of expertise in their respective domains. Their vast experience and diverse professional expertise provide a thorough RCA.
2) The experts were briefed on the criteria of frugality (inclusion, performance, sustainability, and functional). They were led through the interloop and intra-loop frugal product design lifecycle models, encouraging them to consider possible failure points at each phase. In order to obtain a thorough understanding, team members from various functional areas provided responses that offered a range of viewpoints on possible challenges in frugal design.
3) Both intra-loop (manufacturing to raw material extraction, end-of-life to raw material extraction) and inter-loop (raw material extraction, manufacturing, transportation, installation, use, and end-of-life) phases were used to classify the gathered responses. This classification aimed to find significant problems and recurring trends within particular lifespan phases. A box-and-arrow diagram was used to visually portray the results, emphasizing the primary issue area: the failure of the frugal design.
4) A thorough root cause analysis was carried out to investigate the detected issue further. This required generating ideas and investigating possible reasons why frugal design failed. Fig. 6.3 shows a fishbone diagram displaying the sub-causes and thoroughly summarizes the primary and contributory factors.

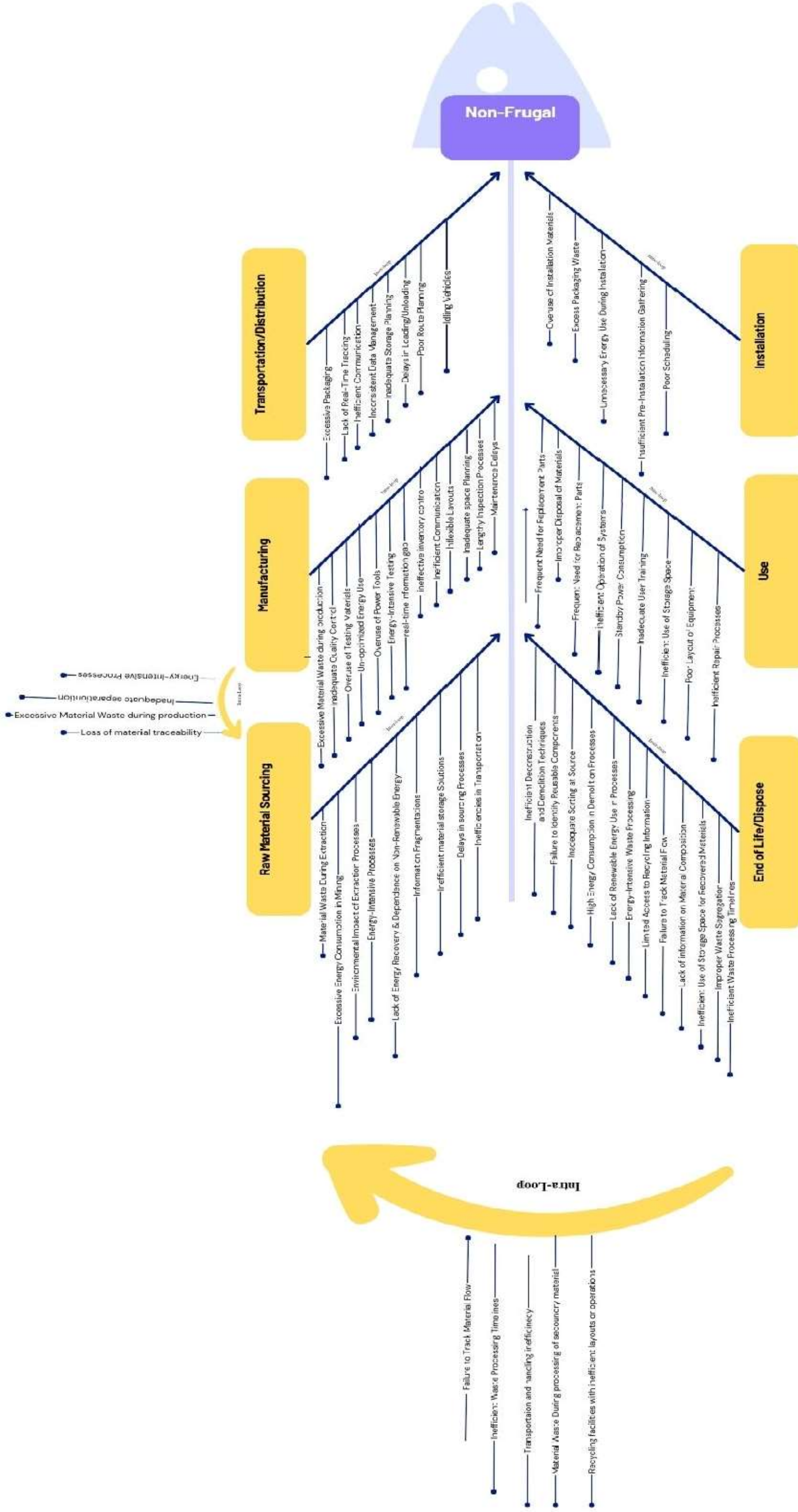


Fig. 6.3. Ishikawa diagram method

6.4.2 Step 2: Prioritization of Sub-causes

Prioritizing the leading causes and their associated sub-causes is the next step after identifying them via a tool such as a Fishbone diagram. This setting of priorities aids in concentrating attention on the areas that need development the most. To concentrate attention on the most significant problems, it is crucial to prioritize the sub-causes of frugal design failure. Sub-causes of frugal design failure are prioritized by comparing them to certain factors (impact assessment, frequency analysis, cost-benefit analysis, and risk assessment) to identify the most important ones to address (Barsalou, 2023).

- Impact assessment: To assess the level to which each sub-cause impacts the product's overall frugality, especially concerning frugality criteria (Coskun et al., 2013)
- Frequency analysis: To determine the frequency of each sub-cause, either at various phases of the inter-loop or intra-loop frugal product lifecycle (Mahto and Kumar, 2008).
- Cost-benefit analysis: To determine if the anticipated benefits of addressing each sub-cause balance the costs (Ferrari and Jones, 2012)
- Risk Assessment: To assess the risks connected with each sub-cause, mainly if left unresolved (Card et al., 2012).

Four factors were prioritized and ranked according to the weights. The Analytical Hierarchy Process (AHP) provides the weightage for the factors. Pairwise comparisons are made at every level of the hierarchy by AHP to distinguish the importance of the factors, and relative weights, also known as priorities, are calculated. Saaty proposed AHP in 1980 (Ashour and Mahdiyar, 2024).

In AHP, the diverse experts were instructed to assess the significance of the factors to prioritize the sub-causes that lead to frugal design failure using a Likert scale (ranging from 1 to 9) through paired comparisons. The normalized Eigenvector of the matrix results in the priority vector (PV), as shown in Table 6.1. The ratio of the random index (RI) to the consistency index (CI) is known as the consistency ratio (CR) see equations 6.1 and 6.2. Higher CR implies poor data quality. A CR value of less than 0.1 (10%) is generally desirable.

$$CR = \frac{CI}{RI} \tag{6.1}$$

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{6.2}$$

where λ_{max} denotes the matrix’s highest eigenvalus

Table 6.1: Pair-wise comparison of prioritization factors

	Impact	**Frequency**	**Cost**	**Risk**	**Criteria weight (CW)**	**Weighted sum value (WSV)**	**Ratio= WSV/CW**
Impact	0.30	0.30	0.30	0.30	0.30	1.51	5.03

Frequency	0.19	0.19	0.19	0.19	0.19	0.58	3.05
Cost	0.26	0.26	0.27	0.26	0.27	1.15	4.25
Risk	0.23	0.23	0.22	0.23	0.23	0.86	3.73

Here, CR 0.006, CR<< 0.01(Standard consistency ratio), the Matrix is consistent, and the priority of factors was determined and weighted with the help of the AHP method. Table 6.2 indicates that the weight (%) of impact (30), Frequency (19), Cost-benefit (27), and Risk (23), and that the consistency ratio (CR) is less than 10%, respectively.

Table 6.2: Weightage of prioritization factors

Priority factors	Impact Assessment	Frequency analysis	Cost-benefit analysis	Risk assessment
Weight (%)	30	19	22	23

6.4.2.1 Perform the prioritization of the sub-causes:

The experts were asked to rate the sub-causes concerning the priority factors on a 5-point Likert scale. Once the Likert-type scale was used to gather data, the rating submitted by participants was included within the proposed prioritization formula (see equation 6.3). The corresponding Priority scores of root causes of the interloop and intra-loop frugal product lifecycle model obtained from this computation are shown in Table 6.3 and Table 6.4.

$$\text{Priority}[A] = (w_{IA}.\ \bar{X}_{IA}) + (w_{FA}.\ \bar{X}_{FA}\text{FA}) + (w_{CBA}.\ \bar{X}_{CBA}\text{CBA}) + (w_{RA}.\bar{X}_{RA}) \qquad (6.3)$$

The research employs fuzzy logic to establish the categorization of the priority score, which ranges from 0 to 5. Fuzzy logic is a potent methodology to manage subjective judgments and uncertainty in decision-making processes (Maretto et al., 2022). Triangular membership functions were used to build fuzzy sets for the categories of priority score "low," "medium," and "High."

$$\text{Priority [A]} = \begin{Bmatrix} Low & if\ 1 \leq A < 2.6 \\ Medium & if\ 2.6 \leq A < 3.6 \\ High & if\ 3.6 \leq A \leq 5 \end{Bmatrix} \qquad (6.4)$$

Table 6.3: Inter-loop frugal lifecycle model Root-cause priority table

Category	Sub-causes	Impact (0.30)	Frequency (0.20)	Cost (0.27)	Risk (0.23)	Priority score	Prioritization
Raw material Extraction	Material Waste during Extraction	4	2	4	4	3.58	High
	Excessive energy consumption in mining	5	2	4	5	4.11	High
	Environmental impact of the extraction process	3	3	2	3	2.7	Medium
	Energy-intensive process	4	3	4	4	3.77	High
	Lack of energy recovery and and dependence on non-renewable Energy	4	2	4	5	3.81	High
	Information fragmentation	4	1	3	4	3.12	Medium
	Inefficient Material Storage Solution	3	2	4	3	3.05	Medium
	Delays in sourcing processes	4	2	4	3	3.35	Medium
	Inefficiencies in transportation	3	2	3	3	2.78	Medium
Manufacturing	Excessive material waste	4	3	4	4	3.77	High
	Inadequate quality control	3	3	2	3	2.7	Medium
	Overuse of testing material	4	2	3	4	3.31	Medium

	Un-optimized Energy use	3	2	4	4	3.28	Medium
	Overuse of power tool	3	1	2	2	2.09	Low
	Energy-intensive production/testing	4	2	3	3	3.08	Medium
	Real-time information gap	3	2	3	3	2.78	Medium
	effective communication	4	3	4	4	3.77	High
	Inflexible layouts	4	3	4	4	3.77	High
	Inadequate space planning	4	3	4	4	3.77	High
	Lengthy inspection process	3	3	3	3	2.97	Medium
	Maintenance delays	4	2	3	4	3.31	Medium
Transportation	Excessive packaging	4	3	4	4	3.77	High
	Lack of real-time tracking	4	1	3	4	3.12	Medium
	Inefficient communication	3	2	3	4	3.01	Medium
	Inconsistent data management	2	2	3	3	2.48	Low
	Inadequate storage planning	4	3	4	4	3.77	High
	Delsy in loading/unloading	3	2	4	4	3.28	Medium
	Poor route planning	2	1	3	2	2.06	Low
	Idling Vehicles	3	2	3	3	2.78	Medium

Installation	Overuse of installation Materials	5	2	4	4	3.88	High
	Excess Packing Waste	5	2	4	5	4.11	High
	Unnecessary Energy use during Installation	5	3	3	4	3.8	High
	Insufficient Pre-installation Information Gathering	4	3	4	4	3.77	High
	Poor Scheduling	4	2	2	3	2.81	Medium
Use	Frequent need for replacement parts	4	2	4	4	3.58	High
	Improper disposal of material	5	2	4	4	3.88	High
	Inefficient operation of systems	3	2	3	3	2.78	Medium
	Standby Power consumption	3	3	2	3	2.7	Medium
	Inadequate user training	2	1	2	2	1.79	Low
	Inefficient use of storage space	3	3	4	4	3.47	Medium
	Poor layout of equipment	3	2	3	4	3.01	Medium
	Inefficient repair Processes	2	2	2	2	1.98	Low
End of life/Dispose	Inefficient de-construction and demolition Techniques	3	1	2	2	2.09	Low

	Failure to identify reusable components	2	1	2	2	1.79	Low
	Inadequate sorting at the source	2	1	2	2	1.79	Low
	High Energy consumption in demolition processes	4	3	4	4	3.77	Medium
	Lack of renewable energy use in processes	3	3	4	4	3.47	Medium
	Energy-intensive waste processing	4	3	4	4	3.77	High
	Limited access to recycling information	4	4	4	4	3.96	High
	Failure to track material flow	3	2	4	4	3.28	Medium
	Lack of information on material composition	5	2	4	4	3.88	High
	Inefficient use of storage space for recovered materials	4	3	4	4	3.77	High
	Improper waste segregation	2	1	2	2	1.79	Low
	Inefficient waste processing timelines	3	2	3	3	2.78	Medium

Table 6.4: Intra-loop frugal lifecycle model root cause priority table

Category	Sub-causes	Impact (0.30)	Frequency (0.20)	Cost (0.27)	Risk (0.23)	Priority score	Prioritization
Manufacturing to Raw material extraction	Energy intensive process	4	3	4	4	3.77	High
	Inadequate separation	2	1	2	2	1.79	Low
	Excessive material waste during production	4	3	4	4	3.77	High
	Loss of material traceability	2	1	2	2	1.79	Low
End of life to Raw material sourcing	Failure to track material flow	3	2	4	4	3.28	Medium
	Inefficient waste processing timeline	3	2	3	3	2.78	Medium
	Transportation and handling inefficiency	3	3	4	4	3.47	Medium
	Material waste during the processing of secondary material	4	3	4	4	3.77	High
	Recycling facilities with inefficient layouts or operations	2	2	2	2	1.98	Low

After determining the priorities, select the high and medium-level priority score root causes for further analysis using the 5 Whys analysis method. Concentrate on the sub-causes with the highest weighted scores, as these are likely to impact your product or process significantly. This process simplifies the root cause investigation, providing a unified approach to identifying and resolving the underlying issues.

6.4.3 Step 3: Five-Why Method

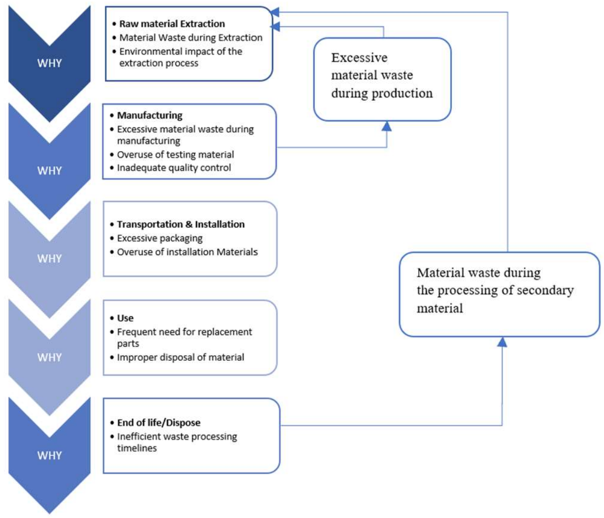
One of the various brainstorming techniques for figuring out "why" is the root cause analysis (RCA), and asking "why" five times is one of the various brainstorming techniques that can be used to find the problem's underlying cause. It is possible to identify a distinct alternative answer for a root cause in each iteration of the problem by asking "why" repeatedly. Until an acceptable or consistent solution that tackles the issue at each phase of the lifecycle is found, this questioning process keeps going. Assuming that the fifth inquiry will probably discover the leading underlying cause (Gangidi, 2019).

The fishbone diagram can incorporate the five-why analysis technique or it can be used separately. In order to investigate all possible or real reasons why frugal design failed, the fishbone diagram was helpful. After placing all input variables in the fishbone, the root causes can be found using the 5-why technique. The authors employed the 5-why analysis technique due to its ability to help identify the problem's underlying cause and establish the connections between the various root causes. Additionally, this method is among the most straightforward and may be quickly completed without statistical analysis.

The authors of this research employed the 5-why analysis technique to pinpoint the main reasons why frugal design failed. Systemic problems that develop throughout a product's lifecycle frequently cause frugal design failures. The overall frugality of a product can be significantly impacted by these problems, which can arise both within certain stages (intra-loop) and across distinct stages (inter-loop). It is essential to formalize these issues in order to address them methodically. These are typical issues that may arise in a frugal lifecycle model during the intra-loop and inter-loop stages.

Asking why these problems occurred and led to frugal design failure, examine the root causes identified in the interloop and intra-loop stages of the frugal product lifecycle model. Focus on high-priority root causes previously identified, as these issues are critical contributors to frugal design failure. Write all these causes below the formalized problem (see Figs. 6.4, 6.5,6.6,6.7, and 6.8). The following most crucial problems and root causes that lead to the failure of frugal design:

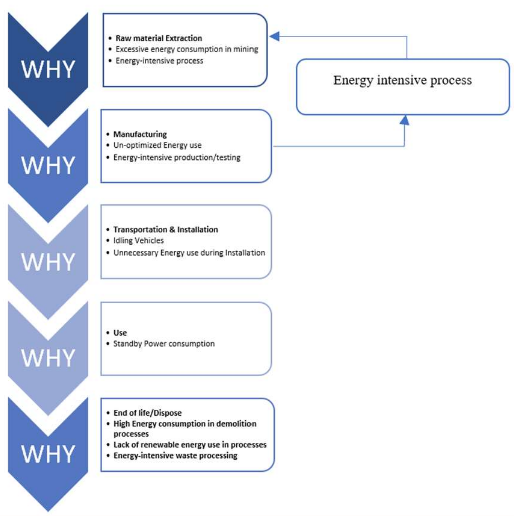
Problem: An ineffective use of materials that substantially negatively impacts the environment and material waste at every stage of a product's life cycle.



Root cause: The inefficient use of materials throughout a product's lifecycle significantly contributes to excessive material waste and adverse environmental effects. This overutilization can take many forms, such as ineffective extraction techniques, inefficient production procedures, improper disposal of material, and packaging waste. As a result, these inefficiencies result in the production of extravagant products that use more resources than necessary, raising cost and leaving a more extensive environmental impact.

Fig. 6.4: Five-Why Methods for material relation problems

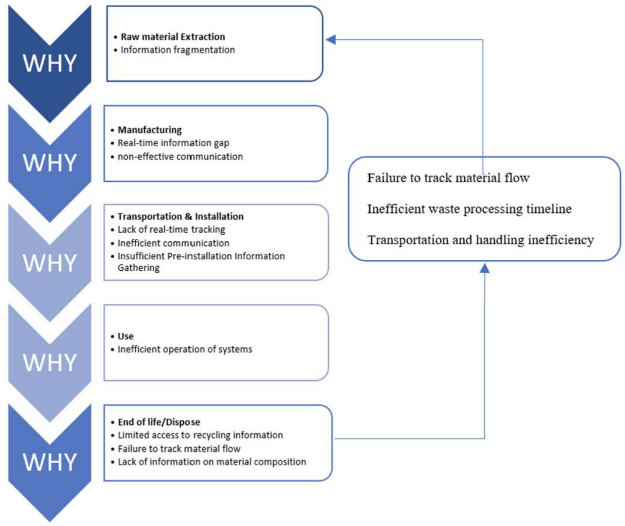
Problem: An energy-intensive production process during the product life cycle stages, increases operational expenses, environmental repercussions, and a diversion from frugal practices.



Root cause: Inefficient energy management throughout the production and utilization process is the root cause of excessive energy consumption and the subsequent non-frugal operations. This inefficiency stems from a number of issues, including inefficient mining methods, excessive energy use during product manufacturing and use, and a need for more thorough energy monitoring. These factors impede energy efficiency, resulting in higher expenses, adverse environmental effects, and a departure from frugal practice.

Fig. 6.5: Five-Why Methods for energy relation problems

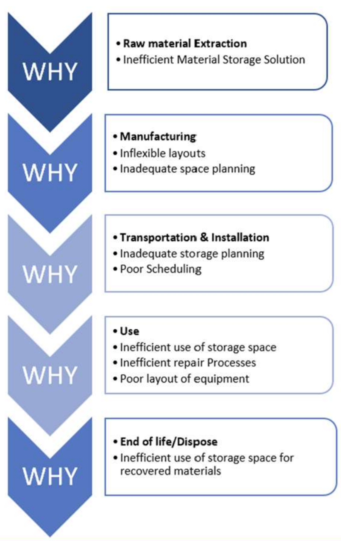
Problem: Inadequate use and management of information, exemplified by fragmentation, poor communication, delayed tracking, and insufficient data collection during the product lifecycle leads to non-frugal solutions.



Root cause: The fundamental source of non-frugal solutions is information inefficiency. Decision-making is hampered by dispersed, out-of-date, or inaccessible information, resulting in inefficient use of resources. The absence of real-time tracking makes it difficult to make timely corrections, which leads to lost chances for advancement. Ineffective communication impedes teamwork and knowledge exchange, resulting in mistakes and needless work. Insufficient pre-installation data collection causes resource waste, more rework, and unanticipated difficulties.

Fig. 6.6: Five-Why Methods for information relation problems

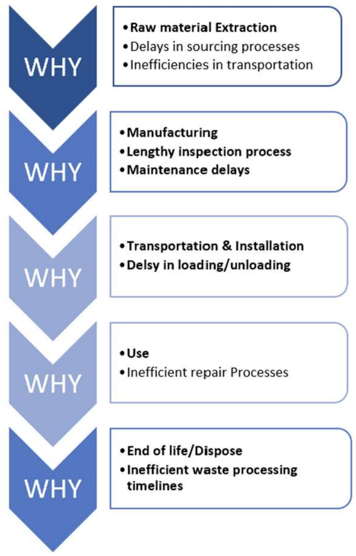
Problem: Significant operational issues are being caused by inefficient material handling and storage procedures. Higher expenses, squandered space, and production or fulfilment delays illustrate these less-than-ideal procedures. Poor storage options, inadequate preparation, inefficient scheduling, rigid facility layouts, and a lack of storage space are all contributing causes.



Root cause: An essential strategic planning and optimization deficiency is the primary cause of underutilized space. The use of less-than-ideal storage systems, careless planning of space capacity, and haphazard material transportation scheduling are examples.

Fig. 6.7: Five-Why Methods for space relation problems

Problem: Process delays can occur at any point in the product lifecycle, resulting in higher costs, longer lead times, and shorter product lifespans. In particular, production delays, inefficient transportation, maintenance procedures, and delays in sourcing all add to overall inefficiencies and non-frugal outcomes.



Root cause: The cause of non-frugal design is largely influenced by lengthy processes. Resources are used inefficiently when it takes longer to source, produce, or repair something. Frugality is undermined by this inefficiency because it results in higher expenses, wastage of resources, and energy use.

Fig. 6.8: Five why Methods for time relation problems

The ineffective use of fundamental input resources (material, energy, information, space, and time) becomes a significant root cause of frugal design failure (see Table 6.5).

Table 6.5: Root cause analysis of frugal design failure

Problems	Root cause	Explanation
An ineffective use of materials that substantially negatively impacts the environment and material waste at every product's life cycle stage.	The inefficient use of materials throughout a product's lifecycle significantly contributes to excessive material waste and adverse environmental effects. This overutilization can take many forms, such as ineffective extraction techniques, inefficient production procedures, improper disposal of material, and packaging waste. As a result, these inefficiencies result in the production of extravagant products that use more resources than necessary,	Material is an essential input into the production of frugal design. Designers can reduce costs and environmental impact by using limited materials and choosing sustainable and recycled materials. Optimized product selection and use to ensure equipment is stable, efficient, and effective

	raising costs and leaving a more extensive environmental impact.	
An energy-intensive production process during the product life cycle stages, increases operational expenses, environmental repercussions, and a diversion from frugal practices.	Inefficient energy management throughout the production and utilization is the root cause of excessive energy consumption and subsequent non-frugal operations. This inefficiency stems from several issues, including inefficient mining methods, excessive energy use during product manufacturing and use, and a need for more thorough energy monitoring. These factors impede energy efficiency, resulting in higher expenses, adverse environmental effects, and a departure from frugal practice.	Energy is another important concept. Energy efficiency and renewable energy help reduce operating costs and lower carbon footprints. Product manufacturers can create efficient and cost-effective solutions by creating products that require less energy and maximize energy efficiency.
Inadequate use and management of information, exemplified by fragmentation, poor communication, delayed tracking, and insufficient data collection during the product lifecycle leads to non-frugal solutions scheduling, rigid facility layouts, and a lack of storage space are all contributing causes.	The fundamental source of non-frugal solutions is information inefficiency. Decision-making is hampered by dispersed, out-of-date, or inaccessible information, resulting in inefficient use of resources. The absence of real-time tracking makes it difficult to make timely corrections, which leads to lost chances for advancement. Ineffective communication impedes teamwork and knowledge exchange, resulting in mistakes and needless work. Insufficient pre-installation data collection causes resource waste, more rework, and unanticipated difficulties.	A key input of frugal design is information. Contextual information, intuitive design, and clear and succinct information improve user experience while lowering maintenance costs. Designers may enable users to get the most out of products and reduce the need for further help by presenting necessary information in a manner that is accessible.
Significant operational issues are being caused by inefficient material handling and storage procedures. Higher expenses, squandered	An essential strategic planning and optimization deficiency is the primary cause of underutilized space. The use of less-than-ideal storage systems, careless planning of	In frugal design, space is a vital input resource. Compact designs, adaptability, and efficient use of space maximize

space, and production or fulfillment delays illustrate these less-than-ideal procedures. Poor storage options, inadequate preparation, inefficient scheduling, rigid facility layouts, and a lack of storage space are all contributing causes.	space capacity, and haphazard material transportation scheduling are examples.	production and transportation procedures. Designers can lower production and logistics costs by optimizing items' functioning inside a given space and lowering their physical footprint.
Process delays can occur at any point in the product lifecycle, resulting in higher costs, longer lead times, and shorter product lifespans. In particular, production delays, inefficient transportation, maintenance procedures, and delays in sourcing all add to overall inefficiencies.	The cause of non-frugal items is influenced mainly by lengthy processes. Resources are used inefficiently when it takes longer to source, produce, or repair something. This inefficiency undermines frugality because it results in higher expenses, wastage of resources, and energy use.	Time includes all aspects of a product's lifecycle, such as manufacture time, use, and lifespan. Time optimization enables efficiency at every level of frugal design, from quick and simple user interactions to swift production processes. A product's durability is also essential to preserving cost because long-lasting items require fewer replacements. However, a limited lifespan, complicated operational processes, or long production schedules can compromise the product's frugal nature. Therefore, it is crucial to balance time concerns while developing sustainable, affordable goods that provide users with long-term value.

Improper use of materials: Improper use throughout a product's life can cause excessive environmental damage. Factors such as poor extraction methods, poor manufacturing methods, poor disposal methods, and improper packaging contribute to overuse. These inefficiencies create expensive products that increase costs and environmental impacts that impact design costs.

Inadequate Energy Administration: Poor energy management during production and usage can lead to excessive energy consumption and cost savings. The benefits include less mining, higher energy requirements in the production process, and less energy maintenance.

Lack of Information: A lack of valid, real-time information leads to poor decision-making and resource utilization. Bad, outdated, or hard-to-access data prevents timely updates and leads to missed opportunities to improve performance. Poor communication and information sharing can hinder collaboration, while failure to gather information in advance can lead to waste, rework, and unnecessary problems.

Information Inefficiency: Unable to access real-time information leads to inefficient decision-making and resource use. Disorganized, outdated, or hard-to-access data obstructs timely adjustments, resulting in missed opportunities for efficiency improvements. Poor communication and data sharing hinder collaboration, while limited pre-installation data collection leads to waste, rework, and unforeseen challenges.

Inefficient use of space: Poor planning and optimization lead to inefficient storage and office space use. Inappropriate storage systems, irregular space planning, and inconsistent transportation can lead to waste and insufficient space, leading to increased costs and transportation disruption, thus deviating from frugality criteria.

Long lead times: Long lead times in manufacturing or repair lead to inefficient use of resources. These delays increase costs, waste resources, and energy consumption, ultimately expanding the environmental and financial footprint of the product's life cycle and leading to frugality goals.

6.5 Summary

This research used a three-stage root cause analysis (RCA) approach to identify and evaluate the causes of frugal design failure. A series of interrelated problems often causes the failure of frugal design, and determining the root causes of these problems is essential to improving frugal design.

This research used various RCA methods developed in the literature, including Fishbone Ishikawa Diagram, Prioritization, and 5-Why Analysis. This tool facilitates the identification and analysis of root causes. The research revealed 56 causes of inter-loop failure and nine causes of intra-loop failure throughout the life cycle of financial equipment. However, 51 causes were identified as the most important causes of failure in the prioritization application. In addition, the Five Whys Analysis categorizes sub-causes into the five leading root causes of frugal design. These are primarily due to the non-optimal utilization of input resources (materials, energy, data, space, and time) throughout the frugal product lifecycle. Improper use of these critical inputs can lead to failure to achieve frugal design goals.

This detailed analysis gives a more profound knowledge of the systemic problems in frugal design and lays the foundation for specific interventions to improve its success.

Chapter 7

Input-Output Analysis Model of Frugal Design

" Output depends on input. If sudden changes occur at the input side, then continuous changes exist in the output"- Pavan Bheemagani.

This chapter presents a novel adaptation of Input-Output Analysis (IO-A) for application in the frugal design domain, aimed at systematically analyzing the correlation between design inputs (material, energy, Information, space, and time) and outputs (sustainability, inclusion, function, and performance). Frugal Design is well established as "More Value with Fewer Resources." However, methodological frameworks cannot quantify and use these relationships. This research uses the IO-A model, which has been traditionally used in economic analysis, to model workflows for frugal design excitation as a fusion of input and output. Canonical Correlation Analysis (CCA) examines the complex relationship between the input and output. CCA is a suitable method for analyzing high-dimensional latitude and correlation data, and it can usually reveal weak correlations and compromises beyond the scope of qualitative analysis. Providing a data-controlled approach for frugal design concept, which enables optimum resource utilization for creating sustainable solutions.

7.1 Introduction

The increasing demand for affordable, accessible, and resource-efficient solutions requires new processes that maximize resource efficiency while maintaining functionality and performance (Duflou et al., 2012). Frugal design has become prominent in this context, providing "More Value with Fewer Resources" (Hedlund et al., 2020)." Frugal design emphasizes optimal resource usage and provides a better user experience, requiring a deeper understanding of the relationship between its design decisions and their benefits (Lim and Fujimoto, 2019). Although the frugal design is a well-known concept, no studies methodologically evaluate the relationship between its inputs and outputs. This inconsistency hindered the development of strategic processes to increase the impact of frugal design and improve resource utilization.

(IO-A), originating from engineering and economic systems, offers a new way to bridge this gap. It is a powerful financial tool traditionally used to analyze economic interdependencies (Leontief, 1987). It provides a basic framework for understanding the input-output relationship in producing frugal products by considering the design process as integrating input and output. The input-output analysis model provides a data-driven approach by mapping and quantifying the relationship between input and output variables. In contrast to conventional qualitative assessments, this method pinpoints essential concepts and their proportionate roles in results to facilitate better decision-making (Koch et al., 2021).
This research is a new approach to using input-output strategies in frugal design; using the method, i.e., of canonical correlation analysis (CCA) method, this research provides clear evidence of the importance of resource development to capture better output. CCA is essential for examining the relationship between input and output

variables of frugal design research (Guo and Wu, 2019). When dealing with high-dimensional correlation data, traditional statistical methods such as multiple regression or Pearson correlation sometimes fail to account for the complexity of the data. CCA addresses these challenges by examining two sets of variables simultaneously, exposing the relationship without assuming a unidirectional influence from input to output (Hardoon et al., 2004). This flexibility is critical for understanding how various inputs collectively differ in design outputs and detecting subtle trade-offs and emergent patterns inherent in resource-constrained situations. As frugal design increasingly relies on data-rich approaches, using CCA enables target resource optimization tactics and helps the development of sustainable and inclusive solutions that address the difficulties of current product design. The author proposed a correlation analysis methodology to investigate the relationships between key concepts in frugal production and output.

7.2 Research Background

The research background is categorized into two parts. First, it discusses the input-output variables of frugal design identified in the previous section, and later discusses the analytical method of canonical correlation analysis (CCA).

7.2.1 Frugal Design Input-Output

Frugal Design has emerged as a valuable approach to providing value to users and entrepreneurs in the current dynamic environment, where limited resources, inclusive development, and technology factors are critical (Le Bas, 2016; Leliveld and Knorringa,2018). Frugal design prioritizes affordability, Functionality, and resource efficiency to reach underserved markets and encourage inclusive innovation (Shahid et al., 2023). It has applications in many areas, such as healthcare, banking, transportation, housing, and education, where limited resources must be fully utilized to meet the needs of the underserved (Pisoni et al., 2018). It aims to close the accessibility gap by ensuring that even those living in less privileged communities can benefit and feel good about themselves (Agarwal and Brem, 2017).

Despite its benefits, many organizations fail to develop frugal designs as they did not fulfill the Output (Sustainability, performance, inclusion, and Functional) throughout their entire lifecycle that we have identified in Chapter 4, with the help of the frugal design evaluation model. The research further performs a comprehensive product lifecycle analysis to uncover the underlying causes of frugal design failure. Using a closed-loop frugal product lifecycle modeling framework and several root cause analysis techniques, this research finds the inefficient use of essential input resources (materials, energy, information, space, and time) as a critical cause of failure identified in Chapter 6. Table 7.1 explains the input and outputs of FD. Correctly processing these inputs is essential for the desired outputs.

Table 7.1: Frugal Design's Input-Output

Input	Output
Material: Material is an essential input into the production of frugal design. Designers can reduce costs and environmental impact by using limited materials and choosing sustainable and recycled materials. Optimized product selection and use to ensure equipment is stable, efficient, and effective	**Sustainability:** This criterion highlights the longevity and ecological footprint of a design. Reduced resource use, waste generation, and detrimental environmental effects are the goals of sustainable frugal design. Frugal design can help create a future with greater environmental responsibility by emphasizing sustainability. It can lessen climate change, stop the loss of natural resources, and support a circular economy.
Energy: Energy is another important concept. Energy efficiency and renewable energy help reduce operating costs and lower carbon footprints. Product manufacturers can create efficient and cost-effective solutions by creating products that require less energy and maximize energy efficiency.	**Functional:** This requirement verifies that a design successfully fulfills its intended function. Practicality, dependability, and the ability to meet user needs are essential elements of a frugal design. The foundation of any effective design is Functional. A frugal product needs to accomplish its intended tasks with minimal resources
Information: A key input of frugal design is information. Contextual information, intuitive design, and clear and succinct information improve user experience while lowering maintenance costs. Designers may enable users to get the most out of products and reduce the need for further help by presenting necessary information in a manner that is accessible.	**Inclusion:** This criterion brings a design's affordability and accessibility into account. People with different backgrounds and skill levels should be able to use a frugal design. It ensures that frugal design helps a broad range of people, especially those who might be marginalized or disadvantaged and who require inclusion. Frugal design can encourage social equity and lessen inequality by taking affordability and accessibility into account.
Space: In frugal design, space is a vital input resource. Compact designs, adaptability, and efficient use of space maximize production and transportation procedures. Designers can lower production and logistics costs by optimizing items' functioning inside a	**Performance:** The criterion assesses a design's efficacy and quality. Despite having fewer resources, a frugal design should produce acceptable performance levels. Performance criteria are essential for a frugal design to be viable and achieve consumer expectations. A well-made, low-cost product can perform

given space and lowering their physical footprint.	better than a more costly one in some aspects, including effectiveness or durability.
Time: Time includes all aspects of a product's lifecycle, such as manufacture time, use, and lifespan. Time optimization enables efficiency at every level of frugal design, from quick and simple user interactions to swift production processes. A product's durability is also essential to preserving cost because long-lasting items require fewer replacements. However, a limited lifespan, complicated operational processes, or long production schedules can compromise the product's frugal nature. Therefore, it is crucial to balance time concerns while developing sustainable, affordable goods that provide users with long-term value.	

7.2.2 Canonical Correlation Analysis

CCA is a popular statistics-based technique developed by H. Hotelling for determining the link between two multi-dimensional datasets or variables (Abdi et al., 2018). CCA is beneficial in frugal design, where input variables (materials, energy, and time) and output variables (cost reduction, sustainability, and accessibility) are multifaceted and interconnected. It allows various variables to be analyzed simultaneously, revealing important connections and measuring how strongly they are interdependent. Examine the linear relationships in CCA between a collection of left-hand x(input) variables x_1, $x_2,\ldots,x_p$ i.e., $V = b_1x_1 + b_2x_2 + \ldots + b_p x_p$, and a set of right-hand $y_1,y_2,\ldots,y_q,$ i.e., $U = a_1y_1 + a_2y_2 + \ldots + a_qy_q.$ The method's main goal is to find several linear combinations of the x and y variables that best capture the correlations between these sets. Canonical variates are the linear composites V and U, and canonical correlation P_1 refers to the correlations between comparable pairs of canonical variates. CCA applies in cases where regression techniques are acceptable, and there is more than one input variable. Jargon plays a significant role in the complexity of CCA: original variables come first, followed by canonical variates and pairs of canonical variates. "variables" refers to the initial variables measured during the investigation. Linear composites of the original variables, one combination on the input side and another on the output side, are canonical variates. These two composites form a pair of canonical variates. Nevertheless, there might be more than one trustworthy pair of canonical variates. Sets of variables on each side(input-output) are merged in canonical correlation to provide a predicted value for each side(input-output) with the highest correlation with the opposite side's predicted value. A broad range of goals can be addressed using CCA (Wang et al.,2020).

- Establishing the degree of any potential links between two sets of variables (measurements taken on the same objects) or, on the other hand, establishing whether two sets of variables are independent of one another. The purpose is to determine the degree of correlation between the two variates in a pair or the strength of the relationship between the variate on the input side of the equation and the variate on the output side (Dos Santos et al., 2014).
- Calculate weights for each set of variables in the input and output sets so that each set's linear combinations have the highest possible correlation (Dos Santos et al., 2014).
- Describe the nature of any connections between the variables in the input-output sets, usually by calculating each variable's proportional contribution to the extracted canonical functions (Dos Santos et al., 2014).

7.3 Materials and Methods

This research aims to comprehend the relationship between frugal design's input and output variables. An IO-A approach is used to thoroughly research and determine the relationship between the frugal design variables.

7.3.1 Data collection

A mixed-methods approach was used to collect data (Leech et al., 2010), including surveys and structured interviews with 50 academic and industry practitioners (i.e., product design, engineering, architecture, academic researchers, and professors). Experts are selected based on their extensive experience in frugal design and development projects, ensuring diverse perspectives and regional representation. Quantitative data were collected in the survey using 5-point Likert-scale questions (see Appendix V) that measured the relationship between input (i.e., material, energy, space, time, and information) and outputs (i.e., sustainability, Functional, performance, and inclusion. This structured approach allows experts to explain how feedback is important with specific examples (Neely et al., 1997). These mixed approaches lead to a robust data collection process that provides depth and context through extensive observations. The research aims to identify crucial input-output relationships by evaluating this data, statistically validate them using canonical correlation analysis, and provide actionable insights for optimizing frugal design processes.

7.3.2 Interpretation of canonical correlation analysis (CCA)

Canonical correlation analysis determines the link between input and output variables (Pearson, 1936). To determine the statistical significance of the canonical correlation coefficients (CCCs), the null and alternative hypotheses are

Null hypothesis $H_0 = p_1 = p_2 = p_r = 0$ (In a frugal design, there is no linear relationship between the set of input variables and the set of output variables.
Or

Alternative hypothesis $H_1 = p_i \neq 0$ at least one i = 1, 2,…,r (A positive correlation exists when at least one correlation between input and output variables is different from zero), (r= represent no of canonical covariates)

CCA mode is represented by a linear combination of the input variables in X and another linear combination of the output variables in Y; here, we have p variables in input set X = $(X_1\ X_2 \ldots \ldots \ldots .. X_P)$, q variables in output set Y = $(Y_1\ Y_2 \ldots \ldots \ldots .. Y_q)$, CCA mode is represented by a linear combination of the input variables in X and another linear combination of the output variables in Y, given X and Y of dimensions p and q from the same set of n observations (see Fig. 7.1) (Weenink, 2003).

A)

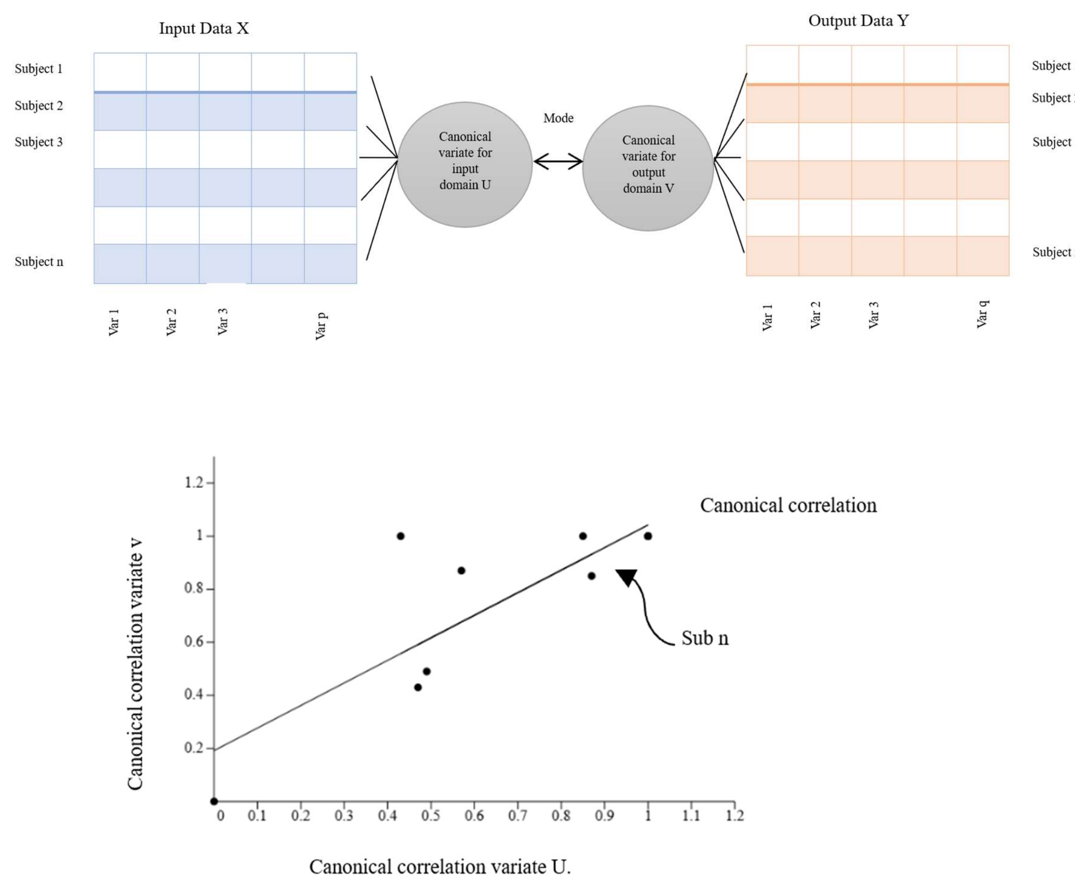


Fig. 7.1: A generic layout for canonical correlation analysis.

A) CCA allows for the co-decomposition of many data domains, each with its own set of p and q variables, measured in the same participant sample. The technique aims to re-express the datasets as several pairs of canonical variates with strong cross-subject correlations. The term "mode" is frequently used to describe each pair of the latent embeddings of the left and right variable sets. B) Two canonical variates per mode, which are maximally correlated as seen in this scatter plot, can thus parsimoniously describe each subject in a two-way CCA setup. Canonical correlation, the primary performance indicator used to estimate a CCA model's parameters, is the linear correspondence between these two canonical variates.

U and V are linear combinations. U corresponds to input (X variables), and V corresponds to output (Y variables). U_1 is the linear combination of the p X variables and V_1 It is the corresponding linear combination of the q Y variable, and so on, as (Ui, Vi) is the ith Canonical variate pair (see equations 7.1 and 7.2). With q≥p, there are q canonical covariate pairs (Weenink, 2003).

$$\begin{bmatrix} U_1 & = & a_{11}X_1 + a_{12}X_2 + \cdots \ldots . a_{1P}X_P \\ U_2 & = & a_{21}X_1 + a_{22}X_2 + \cdots \ldots . a_{2P}X_P \\ U_P & = & a_{P1}X_1 + a_{P2}X_2 + \cdots \ldots . a_{PP}X_P \end{bmatrix} \quad (7.1)$$

$$\begin{bmatrix} V_1 & = & b_{11}Y_1 + b_{12}Y_2 + \cdots \ldots . b_{1q}Y_q \\ V_2 & = & b_{11}Y_1 + b_{12}Y_2 + \cdots \ldots . b_{1q}Y_q \\ V_q & = & b_{q1}Y_1 + b_{q2}Y_2 + \cdots \ldots . b_{qq}Y_q \end{bmatrix} \quad (7.2)$$

Variance of U_i variables with the following expression:

$$\text{Var}\,(U_i) = \sum_{k=1}^{P}\sum_{l=1}^{P} a_{ik}a_{il}\,\text{cov}\,(X_k, X_l) \quad (7.3)$$

The a^{il} through a^{ip} Coefficients in the double sum are identical in the Ui definition. The covariance between the kth and lth x-variables are multiplied by the corresponding coefficients a^{ik} a^{il} For the variables U_i (see equation 7.3) (Weenink, 2003).

An equal computation can be performed for the variance of V_j, as indicated in equation no. 7.4

$$\text{Var}\,(V_j) = \sum_{k=1}^{P}\sum_{l=1}^{q} b_{jk}b_{jl}\,\text{cov}\,(Y_k, Y_l) \quad (7.4)$$

The covariance U_i V_j Between is see equation no. 7.5

$$\text{Cov}\,(U_i, V_j) = \sum_{k=1}^{P}\sum_{l=1}^{q} a_{ik}b_{jl}\,\text{cov}\,(X_k, Y_l) \quad (7.5)$$

The formula (see eq 7.7) is used to determine the correlation between U_i *and* V_j. Divide the covariance between the two variables by the square root of the variance product.

$$\frac{\text{cov}\,(U_i, V_j)}{\sqrt{\text{var}\,(U_i)\text{var}\,(V_j)}} \quad (7.6)$$

The canonical correlation is a particular sort of correlation. The canonical correlation of the i^{th} canonical variate pair is just the correlation between U_i *and* V_i

$$P_i^* = \frac{\text{cov}\,(U_i, V_i)}{\sqrt{\text{var}\,(U_i)\text{var}\,(V_i)}} \quad (7.7)$$

7.3.3 Results and Discussion

In the IO-A model for frugal design, the X variable set contained five input variables (Material, Energy, Information, Space, and time) and output variables (sustainability, Functional, inclusion, and performance). Using the CCA approach, all of the computational work was done to investigate the connections between the two sets of the IO-A model.

Descriptive statistics for the examined variables were performed. Table 7.2, Bivariate correlations displaying the relationships among the I-I variables and O-O variables, I-O variables of frugal design. The highest correlation was predicted between input-input(I-I) variables, time, and space (0.87, $p < 0.05$), and the lower correlation between time and material (0.406, $p < 0.05$) variables. The highest correlation amongst output variables was predicted between performance and space (0.87, $p < 0.05$), and the lower correlation between performance and sustainability (0.244, $p < 0.05$) variables. For input-output (i-o) variables, performance and space (0.84, $p < 0.05$), there is a lower correlation between Time and sustainability (0.29, $p < 0.05$) variables. Since correlation coefficients vary between -1 and 1, all positive values close to 1 indicate a positive correlation between the variables.

Table 7.2: The correlation matrix between Input and output variables

	Material	**Energy**	**Information**	**Space**	**Time**	**Sustainability**	**Inclusion**	**Functional**	**Performance**
Material Pearson correlation Sig(2-tailored)	1	0.681	0.558	0.481	0.406	0.654	0.478	0.401	0.397
Energy Pearson correlation Sig(2-tailored)	0.681	1	0.811	0.691	0.552	0.486	0.750	0.618	0.523
Information Pearson correlation Sig(2-tailored)	0.558	0.811	1	0.832	0.715	0.413	0.675	0.821	0.649
Space (Pearson correlation Sig(2-tailored)	0.481	0.691	0.832	1	0.870	0.373	0.567	0.689	0.772
Time (Pearson correlation	0.406	0.552	0.715	0.870	1	0.292	0.426	0.598	0.840

Sig(2-tailored)									
Sustainability (Pearson correlation Sig(2-tailored)	0.654	0.486	0.413	0.373	0.292	1	0.375	0.282	0.244
Inclusion (Pearson correlation Sig(2-tailored)	0.478	0.750	0.675	0.567	0.426	0.375	1	0.480	0.388
Functional (Pearson correlation Sig(2-tailored)	0.401	0.618	0.821	0.689	0.598	0.282	0.480	1	0.551
Performance (Pearson correlation Sig(2-tailored)	0.397	0.523	0.649	0.772	0.840	0.244	0.388	0.551	1

All canonical correlation coefficients pertaining to the Wilks lambda value were significant (0.927,0.662,0.557, and 0.378 sig. p<0.05), as Table 7.2 demonstrates. Based on these results, we interpreted the relationship between the first pair of canonical variables (U1 and V1), which had a maximum coefficient. Every pair of canonical variates is highly dependent on and connected with every other pair. As the p-values for the first three functions are 0.000 (p<0.05**,** we reject the Null hypothesis, $H_0 = p_1 = p_2 = p_r = 0$ (In a frugal design, there is no linear relationship between the set of input variables and the set of output variables. And accept the alternate hypothesis, $H_1 = p_i \neq 0$ at least one i = 1, 2,…,r (A positive correlation exists when at least one correlation between input and output variables is different from zero), (r= represent no of canonical covariates) for these functions.

Table 7.3: Summary results for the canonical correlation analysis

	Correlation	**Eigenvalue**	**Wilks statistics**	**F**	**Num D.F.**	**Den D.F.**	**Sig.**
1	0.927	6.074	0.047	73.180	20	966.088	0.000
2	0.662	0.780	0.332	33.288	12	722.851	0.000
3	0.557	0.451	0.591	29.375	6	586.000	0.000
4	0.378	0.166	0.857	-	-	-	-

Tables 7.3 and 7.4, in that manner. The canonical coefficient's magnitudes indicate their relative contributions to the associated variate. The coefficients show how inputs of frugal design affect the outputs. Consequently, the standardized canonical coefficients (Table 7.4) can determine the canonical variates (U_1 and V_1) representing the best linear combinations of dependent and independent variables.

U_1 = (-0.81 material) + (-0.163 energy) + (-0.486 Information) + (-0.133 space) +(-0.262)

V_1 = (-0.159 sustainability) + (-0.304 inclusion) +(-0.415 Functional) +(-0.430 performance)

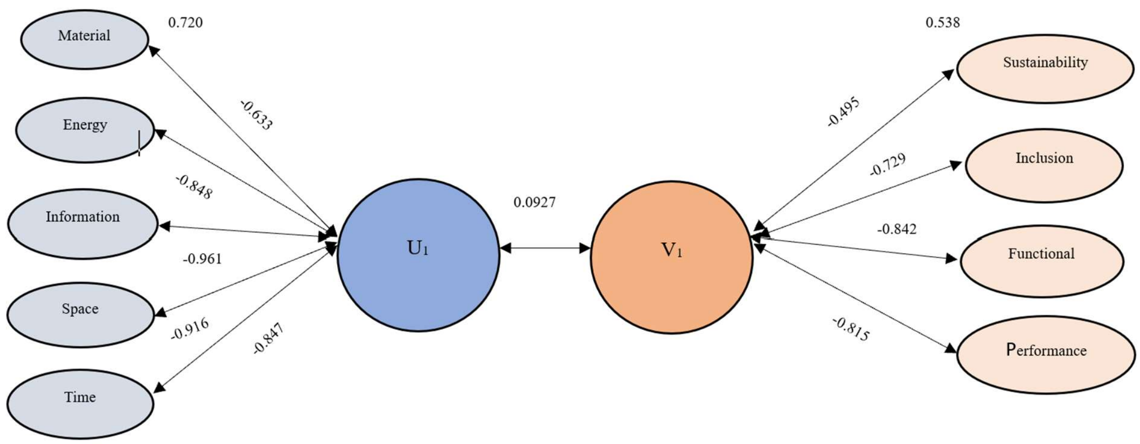


Fig. 7.2: A linear combination between U_1 and V_1 variables

Table 7.4: Standardized canonical coefficients for canonical variables

X variables						Y variables				
	Material	Energy	Information	Space	Time		Sustainability	Inclusion	Functional	performance
U_1	-0.81	-0.163	-0.486	-0.133	-0.262	V_1	-0.159	-0.304	-0.415	-0.430
U2	0.47	-0.444	-0.842	0.061	1.298	V2	-0.106	-0.593	-0.481	1.092
U3	-1.087	-0.233	1.144	-0.263	0.033	V3	-0.945	-0.042	0.708	-0.119
U4	-0.823	1.847	-1.493	0.144	0.302	V4	-0.507	0.999	-0.859	0.301

The input values, therefore, indicate a more significant impact on the frugal design's output. These findings support the notion that the optimal use of input (material, energy, information, space, and time) resources results in output (performance, sustainability, Functional, and inclusion). The multivariate correlations between input and output variables were more heavily influenced by factors with higher canonical loadings (Table 7.5)(see Fig. 7.2). According to the loadings for the output variables, V_1 was formed more by sustainability and inclusion than by Functional and performance. When producing U_1, the material loading had a more significant impact than the other input variables.

Table 7.5: Canonical loadings of the original variables with their canonical variables

X variables						**Y variables**				
	Material	Energy	Information	Space	Time		Sustainability	Inclusion	Functional	performance
U_1	-0.633	-0.847	-0.961	-0.916	-0.847	V_1	-0.495	-0.729	-0.842	-0.815
U_2	-0.169	-0.337	-0.197	0206	0.524	V_2	-0.198	-0.440	-0.195	0.572
U_3	-0.721	-0.209	0.153	0.033	0.052	V_3	-0.791	-0.104	0.355	0.023
U_4	-0.208	0.342	-0.118	0.046	0.046	V_4	-0.301	0.513	-0.357	0.092

Cross-loadings showed that material and sustainability significantly contributed to canonical variates V_1 and U_1, respectively. Nonetheless, the frugal design's input and output variables correlate positively (Table 7.6).

Table 7.6: Cross-loading of the original variables with opposite canonical variables

X variables						**Y variables**				
	Material	Energy	Information	Space	Time		Sustainability	Inclusion	Functional	performance
U_1	-0.586	-0.786	-0.890	-0.849	-0.785	V_1	-0.459	-0.676	-0.780	-0.755
U_2	-0.112	-0.223	-0.131	0.136	0.347	V_2	-0.131	-0.291	-0.129	0.378
U_3	-0.402	-0.117	0.085	0.018	0.029	V_3	-0.441	-0.058	0.198	0.013
U_4	-0.078	0.129	-0.45	0.018	0.017	V_4	-0.114	0.194	-0.135	0.035

According to the current research, all canonical variables Vi accounted for 53.8, 14.9, 19.1, and 12.2% of the total variation in the Y variables. On the other hand, the first canonical variable's redundancy measure of 0.462 indicates that canonical variable U_1 accounted for roughly 46.2% of the ratio. Additionally, it was discovered that the first canonical variable, U_1, accounted for 72.0% of the overall variation in the x variables. On the other hand, the first canonical variable's redundancy measure of 0.619 indicates that canonical variable V_1 accounted for roughly 61.9% of the ratio (Table 7.7).

Table 7.7: The explained total variation ratio by canonical variables for the variable sets

X variables				Y variables			
	Variance extracted		Redundancy		Variance extracted		Redundancy
U_1	0.720	V_1	0.619	V_1	0.538	U_1	0.462
U2	0.1	V2	0.044	V2	0.149	U2	0.065
U3	0.118	V3	0.037	V3	0.191	U3	0.059
U4	0.036	V4	0.005	V4	0.122	U4	0.017

Determining the relationship between input-output variables to create the frugal design illustrates how better output results from using these input resources. In order to do this, this research has uncovered the connections between the frugal design's input variables (material, energy, information, space, and time) and output variables (performance, sustainability, inclusion, and Functional). This research establishes these relationships and provides a basis for further design model development. By identifying these patterns, future research and applications can improve resource utilization to achieve better results and enable more effective and efficient problem-solving. As a new research area, this input-output model makes a significant difference by providing a data-driven approach to assess resource constraints and operational outputs.

7.4 Summary

The increasing need for readily available and resource-efficient solutions emphasizes the necessity of realistic design procedures to preserve functionality and performance. Although frugal design prioritizes resource efficiency, it lacks strategic development because it fails to develop the relationship between inputs and outputs. Through the quantification of the effects of input factors (materials, energy, information, space, and time) on output variables (performance, sustainability, functionality, and inclusion), this research presents Input-Output Analysis (IO-A) as an organized approach to comprehending these relationships. The results show that all canonical correlation coefficients from the Wilks' lambda test were significant (0.927, 0.662, 0.557, and 0.378), indicating strong interdependence among input and output pairs at $p < 0.05$. This means we reject the null hypothesis and accept the alternative hypothesis (a relationship exists between inputs and outputs). It confirms that a positive correlation exists. This research further reaffirms how CCA can be applied to maximize resource use while promoting sustainable and inclusive frugal design solutions.

Chapter 8

Validation of Input-Output Model of Frugal Design Framework

"The logic of validation allows us to move between the two limits of dogmatism and skepticism- Paul Ricoeur."

Frugal design is to create sustainable, functional, inclusive, and resource-efficient solutions by optimizing input variables such as materials, energy, space, time, and information. However, establishing a quantitative relationship between these input variables and frugal design outputs remains challenging. This chapter presents a methodological approach to validating the Input-output model of frugal design by examining five case studies. This research initially records interdependencies between input variables, followed by an analysis of the impact on frugality knowledge, such as sustainability, function, and inclusion. Quantitative verification methods are used to determine the strength and consistency of these relationships. The results provide insight into factors that influence the development of Frugal products and provide a framework for companies that aim to improve the efficiency of their design processes. This research contributes to a broader discourse on sustainable and integrated product development by proposing a structured methodology for assessing the effectiveness of frugal designs.

8.1 Introduction

Frugal design (FD) sprang out of the need for affordability and evolved as a fundamental strategy for generating solutions, particularly in resource-limited circumstances. In essence, frugal design focuses on "maximizing value while minimizing waste," resulting in innovative products and services that are functional and accessible to a broader range of people (Montalbano and Santi, 2023). A key component of any successful design process, including frugal design, is the ability to accurately model and function under real-world situations (Hindocha et al., 2021). This requires the development and validation of an input-output model. These models simplify and represent the complex relationships between design parameters (inputs) and the resulting performance metrics (outputs) (see Fig. 8.1). Accurate model allows designers to fully leverage the design space, optimize the solutions, and foresee the implications of varying design decisions without needing resource-intensive and time-consuming physical prototypes for every iteration (Kumari et. 2023).

Fig. 8.1: Frugal Design I-O model

The frugal design's effectiveness depends on how reliable and robust the proposed input-output Model of the FD framework is. If a specific framework is not validated, it can result in false predictions, misguided design choices, and ultimately unproductive, frugal outputs (Child and Shaw, 2023). The evaluation process is critical to validate that the I-O model reproduces the system behavior accurately. The predictions made by the I-O model are tested against actual case research data. The gap between the estimated and observed values reveals the lack of the I-O model and directs the need to refine the process (Child and Shaw, 2023).

This chapter lays out key elements for validating the input-output model within the context of frugal design. Despite the growing adoption of frugal design principles, many initiatives do not involve a rigorous process that undermines real-world effectiveness. This research offers a methodology for validating this I-O model, highlighting case studies as an effective empirical validation tool. Examining a specific design project, the authors demonstrate how case studies can offer insightful, real-world data to assess the validity and applicability of the input-output model. This research aims to create a more systematic, evidence-based, frugal design philosophy, creating more efficient and sustainable solutions.

8.2 Validation Method

Inglis (2008), asserts that quality frameworks can be verified by comparing the knowledge of experts in the field with relevant research literature or by combining the two methods. Although using literature is acceptable, it might not be enough, particularly in novel situations (Inglis, 2008). So, the research validated the frugal design input-output framework using a mixed-method approach. Assembling stakeholders will help gather their tacit and explicit expert knowledge. Thus, qualitative data(cases) were taken from the literature to validate the framework, and an expert survey (n=15) was conducted.

The case research approach is selected based on the thematic analysis idea. Grounded theory concepts and deductive matrix analysis can be combined using this approach (Corbin and Strauss, 1990). Grounded theory is an approach that focuses on developing conceptual frameworks through inductive research of the data (Charmaz, 2006). The following are the phases used to validate the framework.

8.2.1 Phase 1: Selection of Case Studies

The seven cases (Modular pre-fabricated housing, Hand-cranked washing machines, 3D printed prosthetics, vertical gardening, Aeroplane, Handheld ultrasound scanner, and modular furniture) were selected to validate the framework. These case studies illustrate how qualitative and quantitative methods may be mixed in the cross-cultural validation and subsequent framework revision (Karasz and Singelis, 2009). These cases represent several application areas, ranging from basic human needs such as living space and health care to exceeding the limits of innovation in transportation and agriculture research. This diversity enables a comprehensive analysis of framework applicability at various scales, user groups, and technical fields. Additionally, these cases facilitate robust quantitative analysis of the effects of frames on various aspects of the frugal design, including resource optimization. The combined findings from these various cases form a strong foundation to validate the framework.

8.2.1.1 Strategic Decision-Making Matrix

Decision matrices were important qualitative instruments to ensure a rigorous and transparent case research selection process (Nasab and Milani, 2012). This matrix allowed us to quickly evaluate potential case studies with predefined criteria directly related to the scope and goals of the framework. Criteria for relevance, diversity, effectiveness, and feasibility were explicitly selected to document the key features of appropriate case studies (Nasab and Milani, 2012). Fifteen experts with relevant knowledge and experience were selected to review the potential cases. On a 5-point Likert scale, these experts evaluated cases on the four criteria (Joshi et al., 2015). Collected Likert data representing expert reviews were systematically included in the decision matrix. Combining expert judgment with a clear evaluation frame, this structured approach allows for a comprehensive comparative analysis of the case studies. By visualizing the expert's evaluations within the matrix, the research quickly identifies the most important and compelling cases best suited to the frame goals and prioritizes them for further testing. Table 8.1 shows that the final cases were selected for this research based on the highest total value (Modular pre-fabricated housing, 3d printed prosthetics, vertical gardening, aeroplane, and modular furniture). This process ensured that selected case studies provided the richest and most relevant data to validate and refine the framework. The research identified five cases for validation (see Fig. 8.2).

Table 8.1: Case research decision matrix

Cases	Criteria's				Score	Selected
	Relevance	Diversity	Effectiveness	Feasibility		
Modular Pre-fabricated Housing	5	4	4	4	17	Yes
3D printed prosthetic	5	4	3	4	16	Yes
Hand-cranked washing machines	2	3	2	2	9	No
Vertical gardening	4	4	3	3	16	Yes
Modular furniture	5	5	4	4	18	Yes
Aeroplane	4	5	4	3	16	Yes
Handheld ultrasound scanner	2	3	3	2	10	No

a) Modular pre-fabricated housing

b) 3D Printed Prosthetics

c) vertical gardening

d) Aeroplane

e) Modular furniture

Fig 8.2 Case Studies

8.2.2 Phase 2: Data Collection

This research includes experts in related fields who are target participants in data collection. The authors adopted a stratified selection technique to assign participants and narrow the sample according to two important criteria, i.e., Experience Level and Case Category, to get more targeted data (Singh et al., 1996). Divide the target participants into five case-based strata to gather the experts' experiences from various cases. Additionally, classify each case research category based on the duration of the experience. To be eligible, participants must have at least a year of practical application experience and direct experience with situations that meet the framework's evaluation criteria. As a result, participants are guaranteed enough time to generate informed opinions about the input (material, energy, information, space, and time) and output (performance, sustainability, inclusion, and function). Thirty experts were involved in the research to deepen the validation process: fifteen from Phase 1 (to ensure continuity of insights) and fifteen new experts (to diversify perspectives and limit potential bias). This extension increases the evaluation's empirical base, encompassing a greater variety of experiential information and strengthening the framework's validity.

For the research, a survey instrument included scenario-based questions (see Appendix VI). A multi-mode format was used for the survey. Scenario-based questions were disseminated via online and paper surveys (Liang et al., 2006). Additionally, the survey was made available in English to boost user participation and enhance the precision of the information gathered. On a 5-point Likert scale, participants are asked to rate the input and output of frugal design in real-world situations to share their product usage experiences.

8.2.3 Phase 3: Data Analysis

To perform the frugal design framework validation, the collected data were organized and analyzed using descriptive and inferential statistics techniques after participant reviews were collected through a Likert scale rating (Statistics, 2013). Descriptive statistics include participants' responses, including mean, median, and standard deviation for all inputs and outputs. An overview of the following has been provided. These measures helped to summarize trends, identify central trends, and recognize variation across case studies (see Table 8.2).

Modular prefabricated homes have the highest information ratings (average = 4.8, SD = 0.4) and performance (average = 4.2, SD = 0.74), indicating vigorous information exchange and overall effectiveness. However, the time efficiency (average = 3.8, SD = 0.74) is average, indicating little execution delay.

A balanced review was presented for the 3D-printed prosthetics, which rated the highest spatial use (average = 4.1, SD = 0.94). However, sustainability (average = 3.4, SD = 0.8) received the lowest score. This reflects concerns about long-term viability. Vertical gardening was moderately consistent and best with information (average = 4.0, SD = 0.77), but slightly lower in functionality (average = 3.6, SD = 0.91).

Airplanes have emerged in space use (average = 4.5, SD = 0.5) but with the lowest inclusion rating (average = 3.3, SD = 1.0), highlighting the accessibility challenges. Modular furniture was highly rated for information (average = 4.2, SD = 0.87) and performance (average = 4.0, SD = 1.0), but was shown to be less energy efficient (average = 3.8; SD = 0, 87).

In central tendencies (Median and median highlight differences between case studies. Modular furniture (mean = 4.1, median = 4) had the highest material efficiency, while 3D printed prosthetics (mean = 3.5, median = 3.5) had the lowest. Energy efficiency was for aircraft (average = 4.0, SD = 0.77) and modular housing (average = 4.0, SD = 1.0), while Modular furniture (average = 3.8, SD = 0.87) was slightly lower.

For output metrics, Modular furniture sustainability was the most (mean = 3.9, SD = 0.53) but the weakest in 3D printed prosthetics (mean = 3.4, SD = 0.8). Features were Modular furniture (mean = 4.1, SD = 0.94), modular housing (mean = 3.7, SD = 1.0), and vertical gardening (mean = 3.6, SD = 0, 91), classified as the lowest classification. The inclusion values were significantly different, with aircraft (average = 3.3, SD = 1.0) rated at the lowest.

In variability (The standard deviation (SD) value indicates expert agreement or disagreement. Low variability (SD=0.5) suggests the strong agreement observed in modular housing information (SD = 0.4) and aircraft space use (SD = 0.5). Most other categories experienced moderate variability (SDs of 0.5-0.9). This indicates a specific variation but is a consensus.

High variability (SD = 1.0) in airplane inclusion (SD = 1.0) and modular apartment features (SD = 1.0) were found. This shows the opinions of different experts. The sustainability of modular living spaces (SD = 1.0) had the highest deviations, indicating different perspectives of its ecological and economic impacts.

Table 8.2 Descriptive analysis of cases

Cases	**Input**					**Output**			
	Material	**Energy**	**Information**	**Space**	**Time**	**Sustainability**	**Functional**	**Inclusion**	**Performance**
Modular Pre-fabricated Housing	Mean=4 Median=4 S.D. =1	Mean=4 Median=4 S.D. =0.77	Mean=4.8 Median=5 S.D. =0.4	Mean=4.1 Median=4 S.D. =0.83	Mean =3.8 Median=4 S.D. =0.74	Mean=3.8 Median=4 S.D. =1	Mean=3.7 Median=4 S.D. =1	Mean =4.2 Median=4 S.D. =0.6	Mean=4.2 Median =4 S.D. =0.74

3D Printed Prosthetics	Mean=3.5 Median=3.5 S.D. =0.5	Mean=3.8 Median=4 S.D. =0.74	Mean=3.8 Median=4 S.D. =0.6	Mean=4.1 Median=4.5 S.D. =0.94	Mean=3.9 Median=4 S.D. =0.83	Mean=3.4 Median=3 S.D. =0.8	Mean=3.6 Median=3.5 S.D. =1	Mean=4 Median=4 S.D. =0.77	Mean=3.7 Median=4 S.D. =1
Vertical Gardening	Mean=3.8 Median=4 S.D. =0.74	Mean=3.8 Median=4 S.D. =0.74	Mean=4 Median=4 S.D. =0.77	Mean=3.8 Median=4 S.D. =0.74	Mean=3.9 Median=4 S.D. =0.83	Mean=3.9 Median=4 S.D. =0.83	Mean=3.6 Median=3.5 S.D. =0.91	Mean=3.9 Median=4 S.D. =0.83	Mean=3.9 Median=4 S.D. =0.94
Aeroplane	Mean=4 Median=4 S.D. =0.89	Mean=4 Median=4 S.D. =0.77	Mean=3.4 Median=3 S.D. =0.66	Mean=4.5 Median=4.5 S.D. =0.5	Mean=3.7 Median=3 S.D. =0.9	Mean=3.7 Median=4 S.D. =0.9	Mean=3.7 Median=4 S.D. =1	Mean=3.3 Median=4 S.D. =1	Mean=4.2 Median=4 S.D. =0.74
Modular furniture	Mean=4.1 Median=4 S.D. =0.83	Mean=3.8 Median=3.5 S.D. =0.87	Mean=4.2 Median=4.5 S.D. =0.87	Mean=3.9 Median=4 S.D. =0.83	Mean=3.7 Median=4 S.D. =0.64	Mean=3.9 Median=4 S.D. =0.53	Mean=4.1 Median=4 S.D. =0.94	Mean=3.9 Median=4 S.D. =0.94	Mean=4 Median=4 S.D. =1

Additionally, reliability analysis using Cronbach's alpha used internal consistency of responses on the Likert scale to ensure the reliability of measurements (Connelly, 2011). In the summary statistics summary, (see Fig. 8.3). The analysis showed the following alpha values: Modular pre-fabricated housing Cronbach alpha (0.88), 3D printed prosthetics (0.96), Vertical gardening (0.93), Airplane (0.86), Modular furniture (0.93). In all cases, this demonstrates excellent internal consistency and validates the reliability of data collected for analysis.

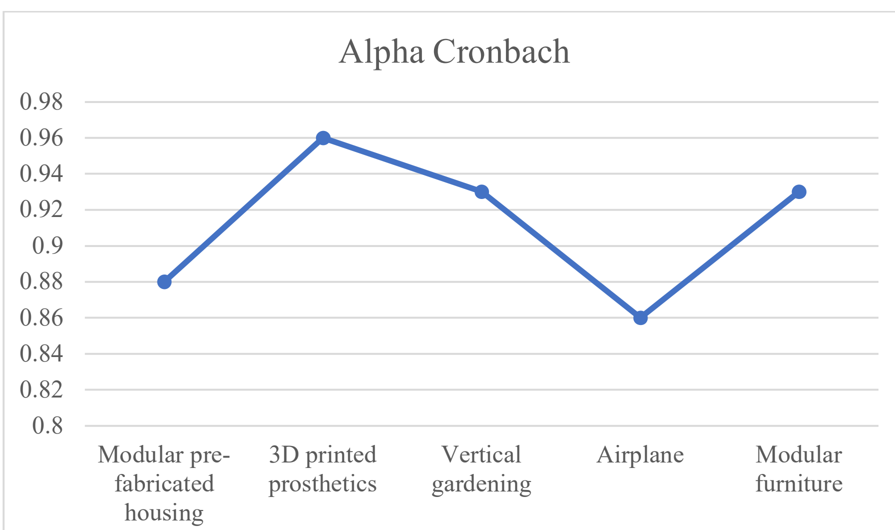


Fig. 8.3: Reliability analysis using Cronbach's alpha

Statistical inference methods such as ANOVA (analysis of variance) were used to determine whether there were statistically significant differences between expert ratings in five case studies (Miller Jr, 1997). The ANOVA analysis is applicable when more than two independent groups are present. Its objective is to see if there is any variation both within and between the groups.

Table 8.3: ANOVA analysis on five case studies

ANOVA						
Source of Variation	**Sum of square (SS)**	**df**	**MS**	**F**	**P-value**	**F crit**
Rows (variation within the groups	82.33	29	1.68	2.484634	7.36E-06	1.386893
Columns (Variation between the group)	36.24	8	4.5	1.154246	0.0325996	1.962034
Error	265.08	392	0.67			
Total	383.65	449				

Rows represent variations between categories of groups (no participant), colors, and variations within groups (input and output groups). Error: They represent random variations within data or inexplicable differences. It is a random or inexplicable variance within the data. The "rows" or "columns" factors do not consider variability. SS (Sum of Squares) measures the total variability of each source of variation. Higher SS values show more significant variability: row 82.33, column 36.24 shows higher variability between and within groups. MS (mean square) is calculated by (MS = SS/DF). Represents the average variance for each source. For rows, P = 7.36E-0.6 <0.05 indicates a statistically significant difference in user ratings for five case studies. This means that users perceive input and output relationships in different ways in some case studies. For columns, p = 0.032 <0.05 indicates that the input variable statistically affects the output variable (Miller Jr, 1997). This supports optimal input use, leading to the desired output (see Table 8.3).

8.2.4 Phase 4: Framework Evaluation and Refinement

Quantitative analyses of five case studies were conducted to assess the validity of the proposed framework. Each case research was assessed based on input variables (materials, energy, information, space, time) and their impact on initial variables (sustainability, function, performance, and inclusion). It shows that all five case studies strongly correlate between optimal use of inputs and the desired outputs of frugal design (see Fig. 8.4 – Fig. 8.8). The proposed framework effectively captures dynamic interactions between input and output variables, increasing the relevance to highly comprehensive frugal product development.

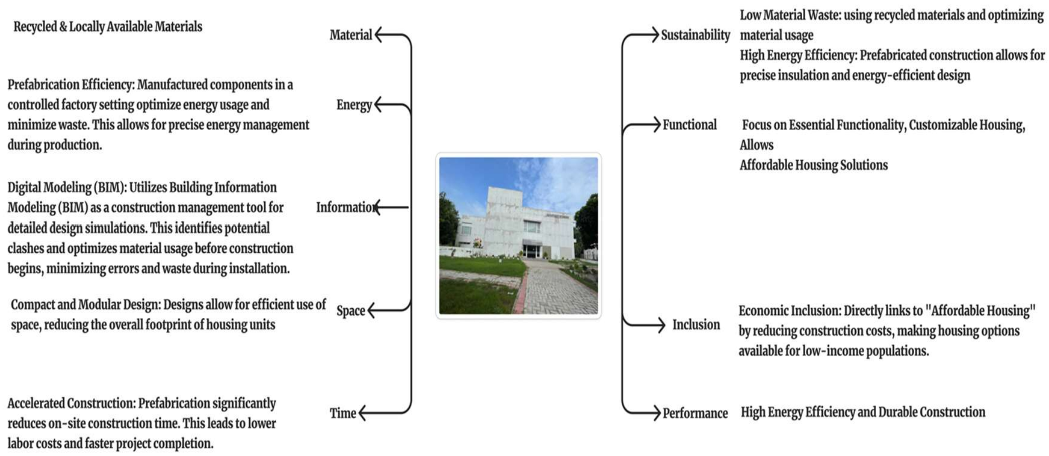


Fig. 8.4: Input-output analysis of Modular Pre-fabricated housing

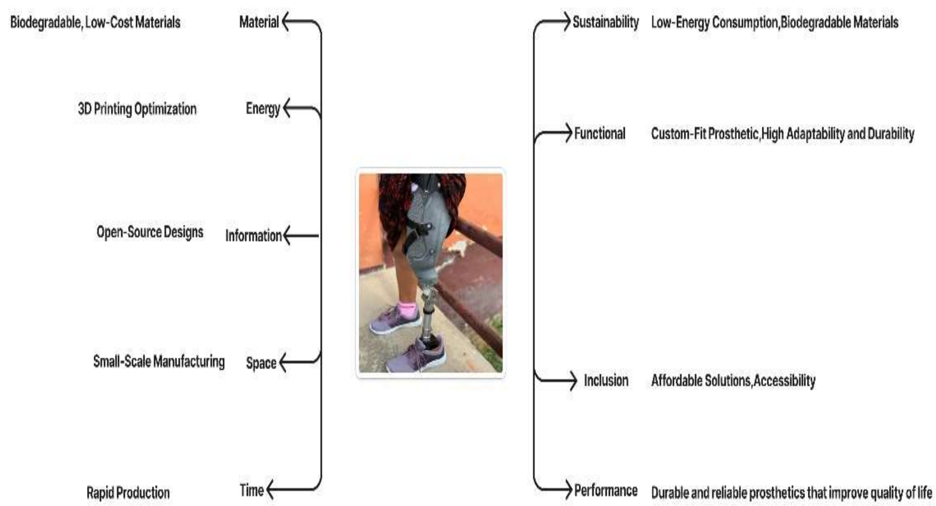


Fig. 8.5: Input-output analysis of 3D printed Prosthetics

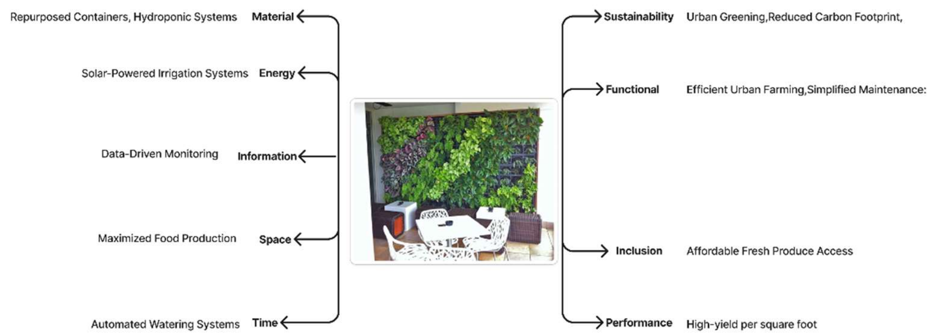


Fig. 8.6: Input-output analysis of Vertical Gardening

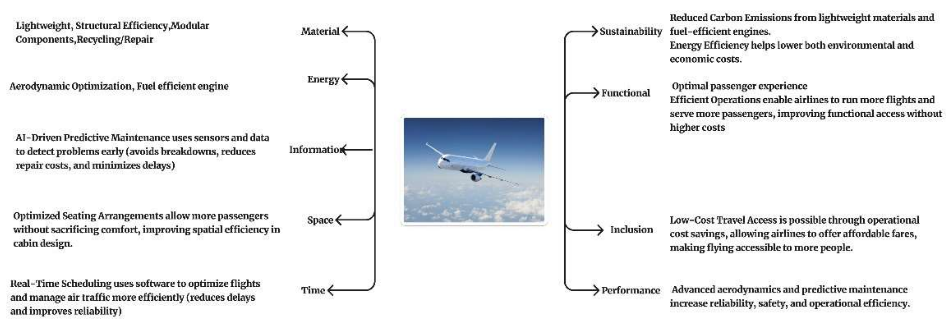


Fig. 8.7: Input-output analysis of Aeroplane

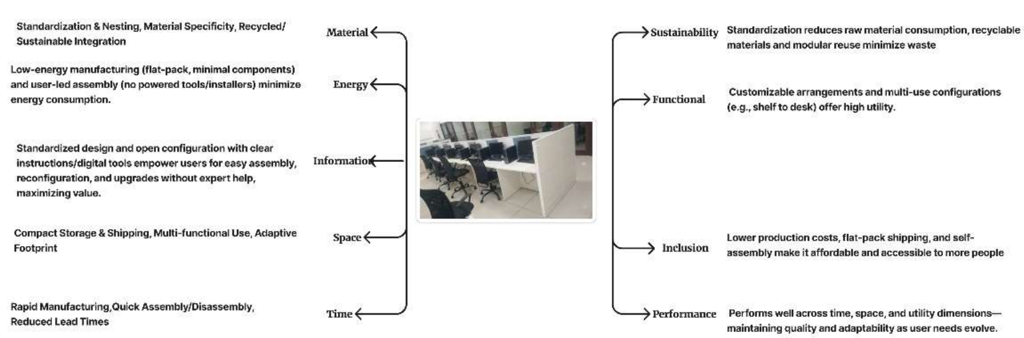


Fig. 8.8: Input-output analysis of Modular furniture

The core structure of the framework is solid and well-verified. Strong correlation and cross-contextuality demonstrate that it effectively captures the essence of frugal design. This means that essential input and output metrics are comprehensive and accurately reflect the dynamics of frugal design. Consistent statistical significance in all five case studies confirms a strong correlation between input and output. Furthermore, slight residual errors in statistical analysis indicate that the FD framework is the most influential factor. However, the core structure requires minimal improvements in the impact of context. In that case, future work should include the moderation of variables to account for variations in I/O relationships across different settings (cultural values, market competition, and regulatory stringency).

A comparison of the work done by earlier researchers to create and assess frugal designs and the designer's contribution to the frugal product design approach is shown in Table 8.4. Parameters such as findings or the framework's strengths and limitations, an assessment of frugal design, and the framework's contribution to frugal design are compared. Table 8.4 makes it evident that earlier frameworks for frugal design and innovation were successful in a specific context but did not expand to a variety of contexts. Despite being conceptual in nature, there is very little evidence of practical implementation. None of the frameworks that were previously examined for comparison include frugality evaluation for the design. A frugality index is also suggested in the proposed IO-FDF to gauge the frugalness of any designed product, in addition to being focused on the input-output variables of the FD.

Table 8.4: Comparison with other frameworks

Author, Year	**Methods**	**Findings**	**Strength**	**Limitation**	**Frugality Evaluation**	**Contribution towards FD**
(Farooq, 2017)	Conceptual Model for Frugal Innovation (CMFI)	Identified the FI Dimension: affordability, simplicity, quality, sustainability, resilience, management support, and defeaturing)	Focus on Sustainability	• This research is conceptual and has no empirical verification • Focusing on the Environmental Economy • Limited scope of case studies	No	Low
(Rossetto and Frankwick, 2018)	Scale for measuring Frugal Innovation	• FI scale development • Identified FI dimensions (affordability, simplicity, and sustainability	• Methodological rigor (EFA and CFA make the scale statistically solid and reliable) • Global Perspective for early-stage scale validation	• Narrowing the scope of FI only focusing on dimensions • Only early validation of the scale is done	No	Moderate

(Rao, 2017)	Advanced Frugal Innovation (AFI),	Defined AFIs from scientific and engineering perspectives	• Focused on AFI with global sustainability goals by highlighting resource conservation and affordability.	It mainly describes theoretical aspects without extensive empirical verification or case studies.	No	Low
(Basu et al., 2013)	Frugal Innovation Core Competencies (FICC)	• Identified the core competencies needed for FI (Adaptability, Affordable, Accessibility) • Focused on sustainability	• Diverse perspective : Explain how FI caters to the sustainability challenges globally • focuses on practical application (healthcare, education, and energy sector	• It is more philosophical; there is no empirical basing behind the findings • it does not explain the specific industries or contexts where FI might have the most significant impact	No	Low
. (Niroumand et al., 2020)	Frugal Innovation Enablers (FIE), [48]	• Identified the 14 “critical enablers” facilitating FI • Examines SMEs engaged within the home appliance manufacturing sector in the Isfahan	• Methodological rigor through mixed methods (literature review, interviews, surveys, and statistical analysis) • The framework is designed for SMEs, making it particularly applicable for organizations that operate in resource-constrained settings.	• It is limited to SMEs in Isfahan province. • A framework is limited to researching the home appliance manufacturing industry. • There is no observation of how these enablers manifest over time or their sustained effect on organizational performance. •	No	Moderate
(Upadhyay and R.M. Punekar , 2023)	The frugal design in marginalized context (FDMC)	• emphasizes affordability, accessibility, and sustainability) of the solutions, ensuring these are meeting the	Designed for marginalized contexts, it is relevant for tackling poverty and inequality in low-resource settings.	• Its theoretical and empirical validation is needed in different contexts to confirm its reliability	No	Low

		most basic needs of marginalized people • includes stakeholders, in addition to local asset-oriented uses •		• It relies on local resources and community participation and may face scaling challenges.		
(Brem et al., 2020)	Frugal New Product Development Process (FNPDP)	Developed a simple new product development (NPD) process and identified key success factors for FI (cost efficiency, simplicity, robustness, and functionality).	This research is based on empirical evidence and provides practical insights into economic NPD processes through real-world case studies and examples.	• The long-term sustainability or scalability of the FI developed using the proposed approach is not examined. • It has been e mpirically ve rified, and the results may n ot apply to all industries or regions due t o differences in market dyn amics.	No	Moderate
(Bhattacharjya et al., 2023)	Community-Led Quadruple Helix FI model (CQH-FI),[58]	This research adapts to a Quadruple helix model (integrating academics, industry, governments, and civil society) to better adapt to the realities of resource-restricted environments in developing countries. Community-guided FI is compiled with a p ositive commitment to local actors contr ibuting to traditiona l and experimental knowledge.	• It focused on marginalized contexts • The focus on intermediaries as facilitators adds depth to understanding how collaboration can be achieved in very stuck ecosystems . • Emphasizing the role of grassroots innovators and local communities thus widens the traditional view of	• The research is based on case studies from Assam, India; hence, generalizing the findings to other countries or spheres may be limited. • The research lacks any substantive quantitative verification or longitudinal empirical evidence.	No	Moderate

			innovation systems.			
(Sharma and Kumar, 2014)	Probing frugal innovation from the quality lens	It explains FI through Garvin's quality lens and highlights performance and compatibility between the eight quality dimensions. It also prioritizes value-based approaches that demonstrate the value promise of economic innovation, promoting operationalization in resource-limited settings.	Mixed methods, including Delphi Focus Groups and Analytical Hierarchical Processes (AHP), ensure robust analysis of quality dimensions.	This research is limited to the construction sector and its generalization can be restricted to other industries.	No	Low
(Girija et al., 2024)	Making frugal innovations inclusive: A gendered approach (IFI),[61]	This research highlights the need to address gender-specific differences in designing and implementing FI. It is emphasized that women have unique challenges in accessing and benefiting from such innovations, especially in resource-related environments.	This research integrates gender analysis into an FI framework and provides a holistic perspective that combines innovation and social justice.	This research can concentrate on a particular sector or region and limit the generalization of recommendations in various contexts.	No	Low
Proposed Framework	Input-output frugal design framework(IO-FDF)	• It emphasizes optimal utilization of resources (materials, energy, Information, Space, and Time), minimizing waste and maximizing value. • Highlighted the key outputs as sustainability, inclusiveness, high performance, and functionality. • Developed the evaluation model to assess why many existing products do not	• integrating various inputs and outputs, the framework provides a comprehensive model of frugal design. • Verification through five case studies ensures that frame adaptability in a variety of industries and contexts • It is consistent with Sustainable Developme	The framework can face challenges in highly specialized or extreme environments where resource limitations and cultural factors differ.	Yes	High

		meet FD criteria. • By examining five different case studies, this framework demonstrates its applicability in a variety of context	nt Goals (SDGs) by focusing on Sustainability and inclusion			

8.3 Summary

This chapter examines the validation of input-output model for frugal design. The research consists of five case studies (Modular pre-fabricated housing, 3d printed prosthetics, vertical gardening, Aeroplane, and Modular furniture), each providing empirical data on how input variables interact with outputs. The validation process involved various phases: (1) Descriptive statistics include participants' responses, including mean, median, and standard deviation for all inputs and outputs. An overview of the following has been provided. These measures helped to summarize trends, identify central trends, and recognize variation across case studies. Additionally, reliability analysis using Cronbach's alpha used internal consistency of responses on the Likert scale to ensure the reliability of measurements. (2) Statistical inference methods, such as ANOVA (analysis of variance), were used to determine whether there were statistically significant differences between expert ratings in five case studies. (3) A comparison of the work done by earlier researchers to create and assess frugal designs and the designer's contribution to the frugal product design approach. Quantitative validation approaches are used to assess the strength of these relationships and ensure a robust framework for understanding frugal design dynamics. By bridging theoretical and practical aspects, this research promotes discourse on sustainable and accessible product innovation.

Chapter 9

Frugal Design Thinking

“Frugal design thinking is not just for emerging markets—it is a mindset for sustainable problem-solving everywhere." — Anil Gupta.

Modern organizations face complex challenges in a dynamic global environment that require innovative solutions. However, the limited resources and the inability to solve complex problems make traditional solutions ineffective. The research introduces the Frugal Design Thinking (FDT) framework as a new method to solve complex manufacturing problems in resource-limited regions. Combining Design Thinking (DT) and Frugal Design (FD), the framework addresses creating affordable, practical, and sustainable solutions without compromising functionality and user-centricity. The research identified four key attributes of FDT: sustainable user-centric design, functional problem framing, inclusive iterative process, and rational performance design. It also used expert input and the analytical hierarchy process (AHP) analysis to determine their relative importance. Furthermore, the research develops a structured evaluation methodology and a quantitative formula to assess products' alignment with these attributes, incorporating real-world user feedback and scenario-based surveys.

9.1 Introduction

In the modern context, Organizations face many complex challenges in the changing global landscape that demand creative solutions (Miles et al., 2010). However, many resources are required to implement these creative solutions. A solution that maximizes impact while minimizing resource usage is urgently needed for emerging countries dealing with affordability and sustainability issues (Lacy et al., 2009). In this scenario, traditional problem-solving methods frequently fail because they either ignore the more considerable complexity of systems or do not minimize the utilization of limited resources (Oliveira et al., 2020). Therefore, developing a method that overcomes these challenges is essential to produce sustainable solutions that benefit the local context and the larger environment.

Design Thinking (DT) is a well-established method that organizations adopt to address difficulties while encouraging innovation and creativity (Brown, 2008). DT can be differentiated from other methods, which are solely analytical, by its intuitive nature (Mansoori and Lackeus, 2020). Through DT, values for new products or services are offered, with an intense focus on the demands of the users (Brown, 2008). The identification of future user requirements is presumed to be enabled by immersion in the user scenario. Better decision-making is another advantage, as is the decrease in cognitive biases (Liedtka, 2015), changing organizational culture to promote innovation (Elsbach and Stigliani, 2018), and nurturing the effects of learning (Beckman and Barry, 2007). DT is widely adopted in practice and has shown promise in promoting human-centered innovation and creativity (Johansson et al., 2013). Nevertheless, for all its advantages, design thinking is frequently insufficient to solve problems with limited resources or provide underprivileged communities with affordable and accessible solutions (Martin et al., 2009). To effectively address the requirements of current global concerns, such methods that emphasize resource efficiency and affordability must be combined with an emphasis on creativity and user-centric design, both of which are valuable (Liedtka,2011).

The research proposed the Frugal Design Thinking (FDT) framework to address these challenges. The Frugal Design Thinking (FDT) framework is a shift toward a hybrid approach that combines the best aspects of Design Thinking (DT) and Frugal Design (FD). It provides a way to solve complex problems in resource-constrained environments. FDT provides an effective way for organizations to develop solutions that meet the needs of different users while reducing resource use and environmental impact. It supports the creation of resource-efficient design innovations that are economical but also responsible and ethical. By using FDT, organizations can align their work with sustainability goals and create a long-term impact on relationships and solutions.

The proposed framework widens the scope of DT research, invokes its real-life dimensions, inspires change, and provides valuable data to organizations. This aspect expands people's understanding of DT and assists organizations in addressing challenges and solving problems more reasonably and rationally.

9.2 Research Background and Gaps

The research background established the foundational understanding of design thinking and frugal design. Furthermore, it explores the area where research is needed.

9.2.1 Design Thinking

Design thinking originated from a preliminary research conducted in the 1960s (Johansson-Skeoldberg et al., 2013); it is an innovative, collaborative approach that helps decision-makers overcome complexity and create unique solutions based on the user's preferences (Elsbach and Stigliani, 2018). DT is a valuable approach for improving decision-making throughout multiple domains of research (Martin, 2010) (Liedtka, 2015). Many practitioners define DT as a process or mindset (Shapira et al., 2018) (Kolko, 2015), a problem-solving approach (Elsbach and Stigliani, 2018), a disciplined approach (Brown, 2008), a concept (Martin, 2009), an application of procedures and thinking (Seidel and Fixson, 2013). While there is no definitive right or wrong understanding, the various authors approach DT with varying focuses and diverse perspectives.

Several DT process topologies, ranging from three to six phases, have been explored in the literature; Table 9.1 describes them. However, the core concept remains consistent in all process models; models with more phases provide a more thorough dissection or division. Da Silva et al. (2020) state that the DT process has five critical phases: "empathize, define, ideate, prototype, and test." Some phases are divided into sub-phases in other models with more or fewer phases (Elsbach and Stigliani, 2018), (Da Silva et al., 2020), (Beckman and Barry, 2007) (Beverland et al., 2015). In practical implementation, the five-phase D. School model is commonly used (Da Silva et al., 2020). The IDEO model has five phases (Shapira et al., 2017). Usually, the procedures include iterations, enabling moving back and forth between specific phases (Buchanan, 2019).

Table 9.1 Various Design Thinking Models

Author (Reference)	**Design Thinking Phases**					
(Beckman & Barry, 2007)	Observe & notice	Frame & Reframe	Imagine & Design	Make & experiment		
(Brown, 2008)	Inspiration	Ideation		Implementation		
(Beverland et al., 2015)	Destabilization	Define & Develop		Transformation		
(Glen et al., 2015)	Problem Finding	Observation	Visualizatio n/ Sense-making	Ideation	Prototype & Testing	Viability Testing
(Shapira et al., 2017)	Discovery	Interpretation	Ideation	Experimentation	Evolution	
(Da Silva et al., 2020)	Empathize	Define	Ideate	Prototype	Test	
(Liedtka, 2015)	Data Gathering about User Needs	Idea Generation			Testing	

9.2.2 Frugal Design

"Frugal Design" was initially introduced in the early 2010s to indicate a new approach to considering innovation via a "frugality lens"(Pisoni et al., 2018). FD has its roots in emerging markets, where the primary objective is to create affordable and accessible products, services, and systems to fulfill the basic requirements of the most vulnerable users of these markets (Hossain, 2018). At its essence, frugal design focuses on "Doing More with Fewer Resources" in creative ways to achieve objectives more quickly and affordably than would otherwise be feasible. Its aim is not solely to produce affordable solutions but to develop comprehensive solutions that benefit the user's well-being and business efficacy (Prabhu, 2017). The foundation of the frugal design approach emphasizes comprehending user requirements before commencing the design process. Innovators must understand user's requirements for a product or service to effectively find opportunities for less resource consumption without compromising quality or the user experience (Kumari et al., 2023). Using a design thinking strategy, innovators can effectively match resourcefulness strategies with user expectations and experience goals. This ensures the resultant solutions remain viable and attractive to the target audience.

This research highlights some limitations in the practice of design thinking that limit its ability to be used in the context of frugality. The following gaps in the literature were identified.

- Current literature mainly explores design thinking or its applications from business, design, engineering, and product development perspectives (Carr et al.,2010). However, the ability to understand the needs of marginalized communities and provide them with practical solutions remains largely untapped.

- Affordability is overlooked over innovation in design thinking practices (Rosch et al., 2023). Cost-effectiveness must be incorporated as a fundamental design requirement to ensure solutions are available to everyone.
- Design thinking frequently ignores the significance of resource optimization (Papalambros, 2024). It is essential to have a framework that prioritizes sustainable solutions and resource efficiency.

Developing a frugal design thinking framework that enables organizations to produce significant and long-lasting solutions that prioritize cost-effectiveness, actively sympathize with non-affluent groups, optimize resources, and encourage creativity within limitations is essential.

9.3 Research Methodology

This research offers an improved method in direct response to these gaps. The research uses a multi-phase approach to develop the Frugal Design Thinking (FDT) framework. The following is the structure of the methodology:

9.3.1 Identification of Frugal Design Thinking Attributes

The research utilizes the mixed-method approach to identify the reliable and accurate attributes of frugal design thinking (Foroudi and Foroudi, 2023). A five-stage research process is used. A preliminary research is conducted to identify the measuring attributes for both frugal design and design thinking. At this stage, the research included both inclusion and exclusion criteria (Meline, 2006). The deductive approach was generally based on a rigorous literature review on design thinking and frugal design. As a result, attributes of design thinking and frugal design were found. Additionally, inductive methods were applied to quantitative data obtained from preliminary data analysis and frugal design and design thinking at this stage 2 (Lewis, 1971). In stage 3, the content analysis method was employed to refine the attributes. Further, the weights are given to the FD and DT attributes. To determine the connection between frugal design and design thinking and to cultivate frugal design thinking attributes, a relationship mapping is created in stage 5.

Stage 1: Data Collection

The research undertakes a systematic literature evaluation (Kitchenham et al., 2003), which includes various previous investigations. The research began by searching the following databases: Emerald, Wiley, IEEE Explore, ABI, Scopus, ProQuest, EBSCO, Inderscience, Science Direct, Sage, Taylor and Francis, and Web of Science. The search string was "frugal design*, “frugal innovation* " AND "design thinking*" in the title or abstract of peer-reviewed papers published between 1980 and 2024.

This search yielded 515 articles on frugal design and 28,190 on design thinking. A preliminary evaluation of titles and abstracts eliminated numerous papers unrelated to the topic. Furthermore, the articles overlap between databases and outside the assessment area. After the second evaluation, exclude articles that examine specific business practices, the application of design thinking in other research fields, and Some overlapping/similar concepts of frugal design. Finally, the analysis included "252" articles on design thinking and "215" articles on frugal design.

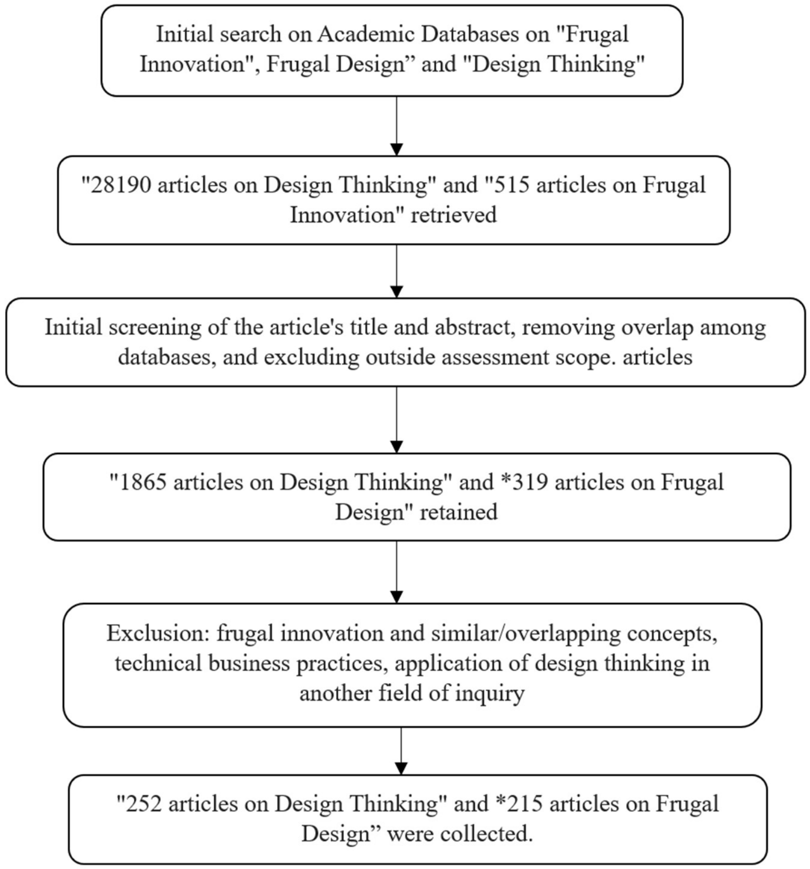


Fig. 9. 1 Data collection process

Stage 2: Data Analysis: Attributes

In this stage, the final collected articles ("252" articles on design thinking and "215" articles on frugal design) were analyzed to identify the attributes related to design thinking and frugal design. These attributes are the common descriptive words (Adjectives) used by academicians and analysts in the literature to represent frugal design and design thinking. Word frequency analyzer software was used to process these articles and calculate the word frequency count of these attributes. The article-specific frequency percentage was calculated for each attribute. The following sections comprise the execution of this task.

1. 8,02,976 words were retrieved from all published papers about frugal design and design thinking.
2. The 519 most often used attributes associated with frugal design and design thinking were chosen for the list.
3. Eliminate attributes not directly connected to frugal design and design thinking to reduce the database cluster's size. The characteristics (such as potential, perspective, and validation) that were not included in the design feature or specification were not included. Similar characteristics were removed, as were those with a word

frequency below 10. Ultimately, the first list of traits related to design thinking and frugal design was created using the thirty attributes (10 of which were related to design thinking and 20 to frugal design), as shown in Table 9.2

Table 9.2 List of most frequently used attributes of Frugal design and Design Thinking

Word (Frugal design)	Frequency	Word Frequency %	Word (Design Thinking)	Frequency	Word Frequency %
Sustainability	293	61.43	Empathy	123	94.61
Affordability	316	81.23	User-centered	120	92.30
Functional	274	70.43	Creativity and innovation	115	88.46
Inclusive	305	78.40	Problem framing and reframing	93	71.53
Simple	261	67.09	Iterative and experimentation	77	59.23
Accessibility	281	72.23	Visualization	59	45.38
Availability	271	69.66	Tolerance of ambiguity	63	48.46
Performance	289	74.29	Interdisciplinary collaboration	42	32.30
Quality	215	55.26	Abduction reasoning	27	20.76
Aesthetics	109	28.02	Rationale and intuitive	34	26.15
Usability	132	33.93			
Environment friendly	191	49.10			
Scalable	104	26.73			
Environmental	118	30.33			
Low-cost	98	25.19			
Ability	43	11.05			
Growing	69	17.73			
Socioeconomic	32	8.2			
Recyclability	31	7.9			
Diverse	26	6.6			

Stage 3: Data Refinement: Attributes

The previously identified attributes of design thinking and frugal design were refined using the content validity analysis method (Mohamad et al., 2015). This test aimed to identify and eliminate any ambiguous or missing information. Twenty experts (professors) rated attributes using a four-point Likert scale, where 1 and 4 represent not essential and highly essential; equation 9.1 was then used to calculate the Item-Content Validity Index (I-CVI) and Content Validity Ratio (CVR).

$$CVR=\frac{Ne-N/2}{N/2} \qquad (9.1)$$

N= number of experts, whereas

N_e = number of experts considering each attribute essential.

Due to their strong CVR (>0.33) and I-CVI score (>0.78), twelve attributes of frugal design and six attributes of design thinking were considered significant. As illustrated in Fig. 9.2, other attributes such as: i.e. Environment-friendly, Scalable, Environmental, Ability, Growing, Socioeconomic, Recyclability, Diverse, Visualization, Tolerance of ambiguity, Interdisciplinary collaboration, and Abduction reasoning were eliminated due to their low CVR (<0.33), and I-CVI score (<0.88), which indicated that most experts did not relate them to frugal design and design thinking (Lawshe, 1975).

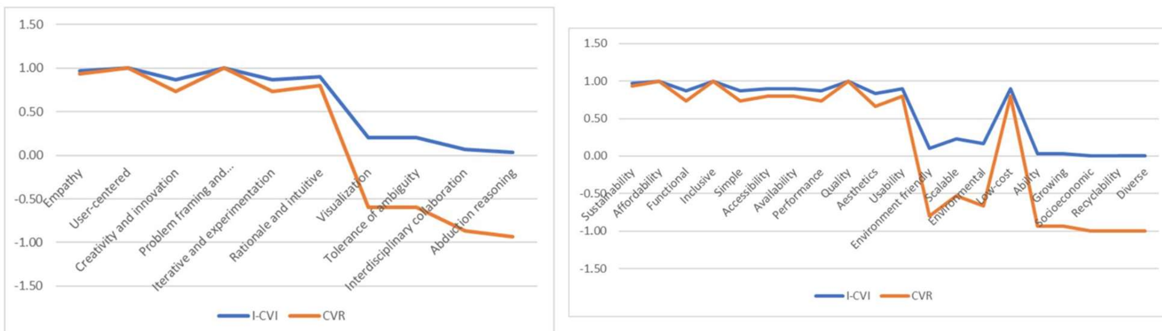


Fig. 9.2: CVR and I-CVI of selected attributes of frugal design thinking

Further, each attribute is categorized and sorted into clusters or themes. Each cluster is assigned a name identifying it as a final frugal design and design thinking attribute. The four main frugal design attributes are (Sustainability, Functional (Usability, simple, Aesthetic), Inclusive (Affordability, Accessibility, Availability), and Performance (Quality), and the four main Design thinking attributes are (User-centered (Empathy), Problem framing and reframing (Creativity and innovation), Iterative and experimentation, and Rationale and intuitive).

Stage 4: Importance of frugal design and design thinking attributes

Assigning weights to FD and DT attributes before determining their relationship and establishing new frugal design thinking attributes is crucial. This ensures that the research is focused on the most important attributes. Organizations can efficiently manage resources, carry out focused research, and make better decisions on their innovation initiatives by prioritizing particular FD and DT attributes. Additionally, weighting can reduce subjectivity and bias, leading to more relevant and objective findings.

The Analytical Hierarchy Process (AHP) provides the weights for both DT and FD attributes. AHP uses pairwise comparisons at every level of the hierarchy of attributes on which it is founded. In 1980, Saaty proposed AHP, a helpful decision-making method (Saty, 2016)

Thirty highly qualified experts with over twenty years of experience in design thinking and frugal design participated in the research. These experts come from various backgrounds, including academicians, designers, engineers, managers, and policymakers. The participants were told to rate the relationship using paired comparisons and a Likert scale (1 to 9) (Joshi et al., 2015). The academicians offer careful analytical and empirical observations, managers explain how frugal design and design thinking are utilized in production processes in the organizations, the designers offer creative and user-focused techniques, the engineers offer vast technical and practical skills, and the policymakers offer regulatory and strategic viewpoints. They offer a comprehensive evaluation of the connection due to their extensive experience and a variety of professional abilities.

Table 9.3 displays the priority vector (PV), the matrix's normalized Eigenvector. The consistency ratio (CR), as shown in equations 9.2 and 9.3, is the ratio of the random index (RI) to the consistency index (CI). A higher CR implies less favorable data quality. In entirety, a CR value of less than 0.1 (10%) is preferred.

.

$$CR = \frac{CI}{RI} \tag{9.2}$$

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{9.3}$$

where λ_{max} represents the greatest eigenvalue in the matrix.

Table 9.3: Pair-wise comparison of frugal design and design thinking attributes

	Sustainability	Functional	Inclusive	Performance	Weighted sum value	Criteria weight/ priority vector (PV)	Ratio= WSV/CW		User-centered	Problem framing and reframing	Iterative and experimentation	Rationale and intuitive	Criteria weight/ priority vector (PV)	Weighted sum value	Ratio= WSV/CW
Sustainability	0.20	0.199	0.2	0.20	1	0.20	5	User-centered	0.35	0.35	0.35	0.35	0.35	1.4	4
Functional	0.30	0.30	0.3	0.30	1.2	0.30	4	Problem framing and reframing	0.27	0.27	0.27	0.268	0.27	1.08	4
Inclusive	0.266	0.265	0.266	0.266	1.08	0.27	3.6	Iterative and experime	0.21	0.21	0.21	0.21	0.21	0.84	4

								ntation						
Performance	0.232	0.234	0.233	0.234	0.92	0.23	4	Rationale and intuitive	0.17	0.17	0.17	0.17	0.17	0.68	4

The AHP method determined and weighed the priority of frugal design and design thinking. In this case, CR = 0.05 for frugal design attributes and CR = 0 for design thinking attributes. The matrix is consistent if CR<< 0.01 (standard consistency ratio).

Here, w_{FD} The weightage to FD attributes are sustainability (0.20), Functional (.30), Inclusive (0.27), and Performance (0.23). and w_{DT} The weights to DT attributes are User-centered (0.35), Problem framing and reframing (0.27), Iterative and experimentation (0.21), and Rationale and intuitive (0.17).

Stage 5: Relationship between frugal design and design thinking

The rising need for sustainable and inclusive solutions that address affordability and resource constraints has created the need to explore the relationship between two domains (frugal design and Design thinking.

The same experts used in the previous stage were used to establish the relationships between FD and DT. Based on this expert feedback, the FDT attributes were given specific weights to ensure consistency and centralize the relationship's most important attributes. This helps emphasize the importance of individual attributes in the overall framework. Table 9.4 explains the frugal Design thinking attributes

Table 9.4: Mapping of Frugal Design Thinking Attributes

	User-centered	**Problem framing and reframing**	**Iterative and experimentation**	**Rationale and intuitive**
Sustainability	Sustainable User-Centric Design: Long-term Sustainable solutions personalized to the user			
Functional	Functional problem framing: Solve real problems, usability, keep it simple			
Inclusive	Inclusive iterative process: Experimentation to craft affordable and accessible solutions.			
Performance	Rational performance design: Solutions developing equilibrium between analytical and intuitive practices.			

$$w_{FDT} = w_{FD}(\mathrm{i}) * w_{DT}(\mathrm{j}) \quad (9.4)$$

$$\text{Normalized } w'_{FDT}(\mathrm{k}) = \frac{w_{FDT}}{\sum_{k=1}^{m} w_{FDT\ (k)}} \quad (9.5)$$

Here, i is the FD attributes matrix, and j is the DT attributes.

Equation 9.4 is used to find the FDT attribute weights, and Equation 9.5 is used to normalize the weight. Normalization provides comparability and consistency by scaling weights to represent the relative relevance of no of attributes (m).

Here, the weights for FDT attributes are Sustainable User-Centric Design (0.28), Functional problem framing (.33), Inclusive iterative process (0.23), and Rational performance design (0.16).

9.4 Development of Frugal Design Thinking Framework

Fig. 9.3 depicts the frugal design thinking Framework. The following procedures must be followed to evaluate the product's adherence to the frugal design thinking attributes.

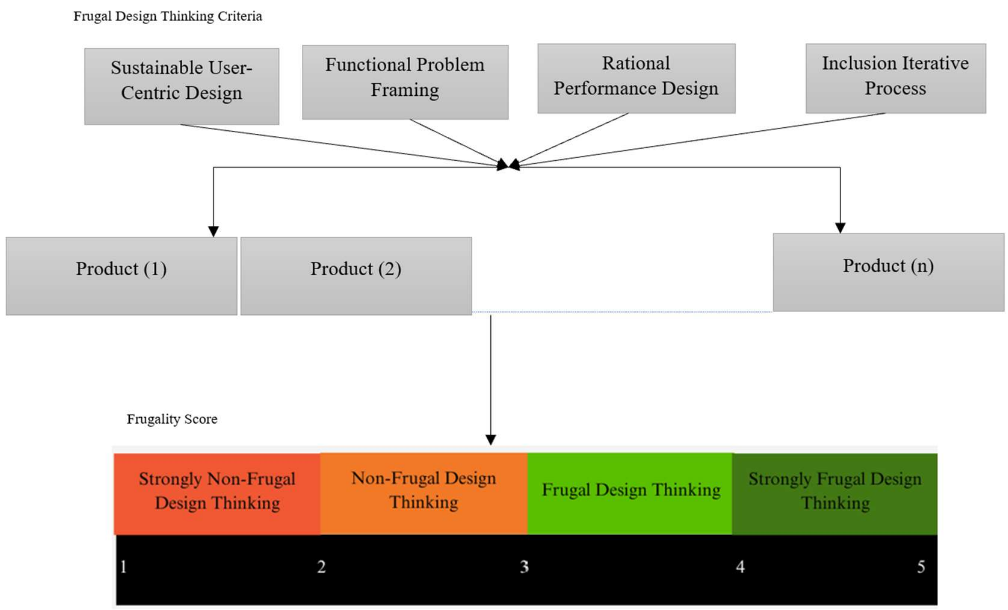


Fig. 9.3: Frugal Design Thinking Framework

Step 1: Choose a product(case) to analyze.

Step 2: Identify the attributes of frugal design thinking to assess certain goods. Sustainable User-Centric Design (0.28), Functional problem framing (0.33), Inclusive iterative process (0.23), and Rational performance design (0.16) are the attributes that are prioritized according to their respective weights.

Step 3: Perform frugal Design Thinking Assessment: The research evaluates how well the product satisfies newly developed frugal Design thinking attributes (e.g., Sustainable User-Centric Design, Functional problem framing, Inclusive iterative process, and Rational performance design) to become sustainable and inclusive design. The research employed products developed by combining design thinking objectives with frugal design to give a valuable framework assessment. Participants are chosen for the research using a stratified selection technique (Tipton et al., 2014). A total of 100 users (20 actual customers of each of these product categories) will participate in the research. On a 5-point Likert scale, the participants were asked to rate the goods according to their experiences and answer scenario-based survey questions (see Appendix VI).

Step 4: The user's mean rating was incorporated into the suggested frugal design thinking score formula after data was collected using Likert-type questionnaires (see equation 9.8). Constructed a matrix [P] for evaluating current products. The matrix $[P]_{s*t}$ Was generated utilizing the Likert scale rates that the user groups gave. Where t stands for columns and s for rows.

$$[P]_{s*t} = \begin{vmatrix} \bar{X}_{11} & \bar{X}_{12} & \bar{X}_{1t} \\ \bar{X}_{21} & \bar{X}_{22} & \bar{X}_{23} \\ \bar{X}_{s1} & \bar{X}_{s2} & \bar{X}_{st} \end{vmatrix} \quad (9.6)$$

The weighted average frugal design thinking score (W'_{FDT}) of the user ratings is calculated by multiplying the weight of each frugal design thinking attribute by the corresponding rating in a matrix that is generated using Equation 9.6.

$$W'_{FDT} = w'_{FDT} \begin{vmatrix} \bar{X}_{11} & \bar{X}_{12} & \bar{X}_{1t} \\ \bar{X}_{21} & \bar{X}_{22} & \bar{X}_{23} \\ \bar{X}_{s1} & \bar{X}_{s2} & \bar{X}_{st} \end{vmatrix} \quad (9.7)$$

A general formula for determining a product's Frugal Design Thinking score is below.

$$\text{Frugal Design Thinking (FDT) Score} = \frac{\sum_{i=1}^{s}\sum_{j=1}^{t} w'_{FDT}\bar{X}_{ij}}{\sum_{j=1}^{n} w'_{FDT}} \quad (9.8)$$

Here, w'_{FDT} Is the weight applied to x values

$\bar{X}_{ij}$ the average user rating value

Step 5: The research uses fuzzy logic to categorize the frugal design thinking score from 1 to 5. Fuzzy logic is a powerful technique for handling ambiguity and subjective assessments in decision-making (Kosko and Isaka, 1993). Fuzzy sets for the FDT score categories "Strongly Non-frugal design thinking,", Non-frugal design thinking", "Frugal design thinking" and "Strongly Frugal design thinking" were constructed using triangular membership functions. Deliberation with a panel of 30 experts was utilized to define the delineations for these categories, ensuring that the classification requirements were valid and accurate (3.1, identify Frugal design thinking attributes). We may successfully consider the products' subjective nature by using fuzzy sets to assess a product's frugal design thinking score. It is possible to assess the degree to which a specific FDT score (a) belongs to each fuzzy set using these membership functions. The products are defined into multiple FDT score categories using the fuzzy sets listed below:

$$\text{DT Score (FDT)} = \begin{Bmatrix} \text{Strongly Non} - \text{Frugal Design Thinking} & \text{if } 1 \leq \text{FDT} < 2 \\ \text{Non} - \text{Frugal Design Thinking} & \text{if } 2 \leq \text{FDT} < 3 \\ \text{Frugal Design Thinking} & \text{if } 3 \leq \text{FDT} < 4 \\ \text{Strongly Frugal Design Thinking} & \text{if } 4 \leq \text{FDT} \leq 5 \end{Bmatrix} \quad (9.9)$$

- Products with an FDT score between 4 and 5 are considered examples of design thinking goals being achieved. Products demonstrate superior performance across all FDT attributes, including sustainability, accessibility, and affordability, ensuring they meet the highest standards of FDT specifications.

- Products with an FDT score between 3 and 4 demonstrate compliance with FDT standards. These products meet some of the features of FDT but do not meet the overall purpose. They are not as straightforward as they seem in providing solutions, but they demonstrate potential for improvement in sustainability and inclusiveness.
- Products with an FDT score range between 2 and 3 are categorized as "non-frugal design thinking." Products in this category exhibit some frugal design thinking characteristics but are generally not regarded as FDT.
- Products with FDT scores between 1 and 2 show poor performance in FDT attributes. They fail to meet basic standards of sustainability and integration and provide cost-effective and practical solutions. Such products fall short of frugal development goals, leading to environmental damage, financial exclusion, or lack of access to resources.

9.5 Assessment of product using FDT framework

This research assesses the extent to which these five products, GE, ECG (Davidson,2015); (Ramdorai and Herstatt, 2015); (Irani, 2010, May 19), Fitbit wearables (Phalkey and Chattapadhyay, 2015). IKEA flat back furniture (Gupta, et al., 2013); (iBAN, 2011, January 1), Oxo Good grip kitchen tools, Remotion Knees (Hamner et al., 2013). purposed to be designed by following the Frugal Design Thinking (FDT) framework in terms of user-friendly, affordable, and inclusive design, as defined within the literature. These products were purposefully selected for evaluation with these objectives in mind. This approach is both practical and informative, allowing for a comprehensive assessment of the product concerning the FDT framework.

Evaluating the FDT framework through product analysis is important to verify its effectiveness in real-world use. By analyzing real-world products, researchers can determine whether the framework supports the development of cost-effective, inclusive, and user-friendly solutions.

The actual users of these products participate in the survey, which makes up the evaluation's target participants. In order to gather more specific information, the authors also use a stratified sampling technique to allocate participants and filter the sample based on two crucial factors: Product Category and Experience Level. Organize target participants into strata based on the five product categories. This allows the collection of user experiences from a wide range of products. Additionally, stratify within each product category based on the length of the customer experience. Only individuals who have used a selected product within that category for at least six months will be eligible for participation. This ensures that participants have enough time to make informed views about the frugal design thinking criteria (Sustainable User-Centric Design, Functional problem framing, Inclusive iterative process, and Rational performance design. The research will involve 100 users (20 real consumers from each product category).

For the research, a survey comprising scenario-based questions was created (see Appendix VI). Scenario-based questions were sent online and offline. Additionally, the survey was made available in both English and regional languages to boost user participation and enhance the precision of the information gathered. In order to answer these questions, participants must rate the frugal design thinking features in real-world situations on a 3-point Likert scale. Each response was converted to a numerical value, and the recommended formula was used. A matrix $[P]_{s*t}$ It was constructed using the ratings the users submitted. Using equation (7), th matrix $[P]_{s*t}$ It is further processed to get the weighted average of frugal design thinking products. In this case, w'_{FDT} is multiplied by the matrix $[P]_{s*t}$.

The FDT score is determined using Formula Equation 9.8, as stated in the approach. Table 9.5 displays the relevant FDT scores of the products derived from this calculation.

Table 9.5 Assessment of products using the FDT framework

Products, reference	**Frugal Design Thinking**				**FDT Score**
	Sustainable User-Centric Design	**Functional problem framing**	**Inclusive iterative process**	**Rational performance design**	$\frac{\sum_{i=1}^{s}\sum_{j=1}^{t} w'_{FDT}\bar{X}_{ij}}{\sum_{j=1}^{n} w'_{FDT}}$
	0.28	0.33	0.23	0.16	
GE, ECG	3	5	3	4	3.82
Fitbit wearables	2	4	2	4	2.98
IKEA flat back furniture	3	4	2	3	3.10
Oxo Good Grips kitchen tools	3	5	5	4	4.28
Remotion Knees	5	5	5	4	4.84

Table 9.5 shows that the FDT scores of the five items range from 2.98 to 4.84, with different FDT levels. Equation 8 divides these categorizations:

Fitbit wearables fall in the non-FDT category, whose FDT score falls between 2 and 3 (see equation 9.9). Data analysis revealed that the designer failed to incorporate the four FDT traits into their design, demonstrating that these products do not comply with FDT as per the proposed framework.

GE, ECG, and IKEA flat back furniture scores between 3 and 4 (see equation 9.9). These products meet some of the features of FDT but do not meet the overall purpose. These products demonstrate potential for improvement in sustainability and inclusiveness

The products (Remotion Knees and Oxo Good Grips kitchen tools) fall between 4 and 5; these products have been observed to follow the FDT attributes. Since these products take into account every FDT attribute that was missed during the previous design process, it has been found that they are solidly FDT (see equation 9.9). By adding these previously ignored FDT attributes, the design of these products is significantly improved. In contrast, a lower FDT score results from the aforementioned products' lack of these attributes. Incorporating FDT attributes early in the design process is critical to creating products that are functional but also sustainable, affordable, and easy to use. By considering resource usage, customer needs, and environmental impact from the outset, designers can optimize assets, reduce waste, and keep users satisfied. Ignoring these attributes can lead to poor performance, increased costs, and missed opportunities for innovation.

9.6 Discussion

Design Thinking is widely recognized for fostering human-centered innovation and creativity, but it often falls short in addressing resource-constrained challenges or providing affordable, accessible solutions for underprivileged communities.

The research proposed the Frugal Design Thinking (FDT) framework to address these challenges. FDT framework is a shift toward a hybrid approach that integrates qualitative insights and quantitative metrics of DT and FD. It provides a way to solve complex problems in resource-constrained environments.

The research makes three contributions by developing a new framework of frugal design thinking. First, it provided the fundamental attributes for frugal design thinking by fusing frugal design and design thinking with word frequency count and content analysis methods. The Analytical Hierarchy Process (AHP) was used to calculate the relative importance (weight) of each attribute (Saty, 2016). Thirty experts from various professions contributed to selecting the attributes to capture practical factors and obtain a variety of viewpoints on the intricate idea. Therefore, the experts gave weight to four primary FDT attributes: sustainable user-centric design, functional problem framing, inclusive iterative process, and rational performance design. A quantitative assessment of the relative importance of each attribute in the quest for effective frugal design thinking in product design was made possible by the weighing process.

Second, the research developed an FDT assessment methodology to evaluate the products after developing frugal design thinking attributes. Products are designed to be by following the FDT attributes used for practical evaluations. We evaluated how effectively each product adhered to frugal design thinking due to this helpful method. The research placed a strong emphasis on quantitative user experience data. To ensure a varied group of participants, the authors employed stratified sampling. Twenty actual customers from each product category were among the 100 users. There was less need for benchmarks because these people used the products under consideration. It ensured that comments were grounded in real-world use. Participants were chosen based on a minimum usage duration of six months to guarantee that user experiences extended beyond the first novelty effects." Subsequent investigations may examine how user opinions of the four FDT attributes have changed during extended product lifecycles. This can provide helpful insight into potential shifts in user priorities as they become more accustomed to the product. The surveys were designed using scenario-based questions (Carroll, 1997). The purpose of the questions was to help participants contextualize their experiences and provide more meaningful precision usage-based responses by placing them in familiar situations.

Third, the research developed a formula for a reliable and easy-to-use assessment of current frugal design thinking product designs. This formula greatly aided in creating an organized method for assessing these products' effectiveness concerning the identified FDT attributes. Therefore, by incorporating these two data sources (qualitative and quantitative) into the formula, the research also addressed a comprehensive evaluation of "frugal design thinking" in product designs.

Overall, the creation of this FDT framework represents a significant advancement in design thinking. This approach gives researchers and industry professionals a methodical, data-driven way to evaluate existing products. The research's theoretical and practical implications are as follows:

9.6.1 Theoretical implications

1. Redefinition of innovation: Innovation has been defined by the FDT framework as a traditional method of product development that prioritizes complex and costly solutions. It offers a novel approach to assessing innovation in addition to technological advancement by taking cost, accessibility, and sustainability into consideration.
2. User-centered approach: FDT is a user-focused methodology. The Foundation ensures that innovation considers not only monetary benefit but also the emotions, consequences, and financial limitations of the target population by fusing design thinking with the importance of user demands and views.
3. Resource efficiency: The framework encourages greater resource efficiency, enabling designers and innovators to be more productive and reduce waste throughout the product's lifecycle.
4. Social Impact: The FDT framework could democratize innovation by facilitating access to underserved communities and promoting social cohesion.

9.6.2 Practical Implications

1. Sustainable business model: The FDT framework enables businesses to create profitable, responsible, and sustainable business models by focusing on resource efficiency and cost-effectiveness.
2. Empowering marginalized communities: The proposed framework enables local communities to participate in the new process, thus creating solutions based on their specific needs and contexts.
3. Development of user-centric Affordable solutions: The FDT framework could create new products and services that low-income people can use to improve their quality of life.
4. Opportunities for innovation: The FDT framework can open new avenues for innovation by encouraging organizations to think outside the box and challenge traditional understandings of product design and construction.

9.7 Summary

The proposed Frugal Design Thinking (FDT) framework provides creative solutions to these challenges by combining elements of Design Thinking (DT) and Frugal Design (FD). This combination emphasizes affordability, accessibility, and sustainability while being functional and user-centric. The research identifies the primary attributes of FDT: sustainable user-centric design, functional problem framing, inclusive iterative process, and rational performance design. Their relative importance is determined using expert-learned techniques and the Heuristic Method (AHP). It also presents an evaluation method that uses real-world products to evaluate against FDT standards. Finally, this research develops a formula that combines qualitative and quantitative data to facilitate the evaluation of products against FDT characteristics.

However, the research acknowledges some limitations. Participating pools are not geographically diverse, and expert selection of FDT attributes may reflect bias. User feedback was collected after six months of using the product, so changes in perception over a more extended period were not investigated. Addressing these limitations through future research, such as conducting longitudinal studies that include a variety of users and involving multiple stakeholders, will improve the impact of the FDT framework. Overall, the FDT framework offers a way to create innovative solutions that are affordable, sustainable, and inclusive, especially for underserved communities.

Chapter 10

CONCLUSION AND FUTURE SCOPE

This chapter provides a summary of the research work completed and ends with a discussion of the work's contributions, future scope, and limitations.

10.1 Summary of the work

This thesis develops the frugal design(FD) framework that leads to the development of frugal products that can be used in a variety of socioeconomic contexts, including developed and developing countries.

The concept of frugal design suffers from a lack of universally recognized definitions, often closely related to low-income emerging countries and populations. This ambiguity hampers wider applications and interdisciplinary possibilities. A more comprehensive and standardized understanding of frugal design is required to promote global adaptability and the full use of its principles for a variety of contexts. This research systematically addresses ambiguity about "frugal design" by developing a clear and universal definition: “A resource-conscious innovation that systematically optimizes the product’s inputs (material, energy, information, space, and time) while rigorously maintaining or enhancing function, performance, inclusion, and sustainability.” The proposed definition accomplishes two goals: it gives practitioners specific recommendations on applying frugal design and its essential attributes, and gives researchers a solid base to construct a cohesive body of knowledge by reviewing existing literature. The research highlights the need for a solid theoretical foundation for frugal design and an extensive assessment of existing definitions. The definition clarifies the intrinsic complexity of FD and its capacity to promote innovation in various industries by cutting costs and reevaluating value propositions.

Following a strong definition of frugal design (FD), the identification of its core attributes is crucial for operationalizing the concept, enabling structured analysis and measurement, creating a workable framework, maintaining consistency and reproducibility, enabling comparative analysis, and ultimately closing the gap between theoretical knowledge and concrete design outcomes. Later, the research identifies the essential attributes of frugal design with the help of Principal Component Analysis (PCA), Content Validity Analysis, and Word Frequency Count. The research presented a framework where four critical attributes of frugal design, i.e., Sustainability, Functionality, Inclusion, and Performance, are identified. The framework also underlines the importance of making the products more frugal for a wider society, including developed and developing countries, and all socioeconomic classes. The identified attributes were validated with the help of the Delphi method in the form of design experimentation. These attributes serve as a fundamental understanding of what makes frugal design. However, simple identification of these attributes is insufficient. A rigorous evaluation model is essential to truly ensure that the design embodies its frugality and achieves its intended effect.

The need for evaluation models arises from the observation that frugal design principles are increasingly recognized, but that their consistent and effective implementation remains a challenge. Existing designs, including frugal ones, often become too short in a particular region, leading to suboptimal results. A frugal design evaluation model(FDEM) has been developed to bridge the gap between theoretical principles and practical applications.

Building this model was a multifaceted process. Initially, a thorough review of existing literature on frugal design was conducted to integrate and refine the criteria (i.e. Sustainability, Functionality, Inclusion, and Performance). Based on this theoretical foundation, this model included empirical data from studies on user experiences involving 200 participants. This user-oriented approach ensured that the model's evaluation criteria reflected real-world perceptions and needs. By integrating theoretical knowledge and practical user feedback, the model provides a comprehensive means of assessing the extent to which a product embodies frugal design standards. This evaluation model allows the identification of areas where design is missing and provides implementation-ready knowledge for improvement. Ultimately, this evaluation model aims to enable designers and businesses to actively embed frugality in the product development process, ensuring that the intended benefits of frugal design are realized.

However, the FDEM evaluates whether the current frugal designs follow the frugality standards or not, but it does not address the important questions. Why do these frugal designs not meet the criteria? The ongoing challenge for many companies in achieving consistent frugal design during production indicates the need for further research. It is not enough to identify symptoms of failure. Instead, it was important to understand the root cause fully. Frugal design is not just an isolated feature, but a systematic approach that permeates every stage of the product's lifecycle. To truly optimize frugal design, there is a need to analyze the complex networks of interactions that influence the outcome. This research performs a comprehensive product lifecycle analysis to uncover the underlying causes of frugal design failure. Using a closed-loop frugal product lifecycle modeling framework and several root cause analysis techniques, this research finds the inefficient use of essential input resources (materials, energy, information, space, and time) as a critical cause of failure. The findings emphasize the importance of a systematic approach to resource management and creating new design solutions to implement frugal design goals successfully. Therefore, advances in FDEM into the framework of root-cause analysis are a logical and necessary step in pursuing highly effective frugal design.

Finally, the thesis introduces novel adaptations of the IO-A (input-output analysis) model that are specifically tailored to the frugal design domain. This adaptation aims to systematically analyze complex correlations between frugal design inputs (materials, energy, information, space, and time) and frugal design outputs (sustainability, inclusion, functionality, and performance). Frugal design is about achieving "More Value with fewer resources," but there was a lack of a methodological framework that could analyze and use these relationships. To resolve this gap, this research proposed the IO-A model. effectively integrating input and output considerations. Canonical Correlation Analysis (CCA) is subsequently used to analyze the multi-faceted interactions between these variables, which expose subtle correlations and trade-offs that qualitative analysis cannot capture. This data-driven method sets the stage for an enhanced frugal design idea that allows for maximum resource utilization in the development of sustainable, holistic solutions. This research carefully documents interdependencies among input variables and their influence on frugality results like sustainability, function, and inclusion. Quantitative validation techniques are used to identify the strength and consistency of the relationships. The ensuing insights provide a basis for companies interested in making their design processes more efficient, part of a larger discussion of sustainable and integrated product development. By suggesting a systematic approach to measuring the effectiveness of frugal designs, this research pushes the practice closer to a more data-driven and effective application of frugal design concepts.

10.2 Contribution of the Thesis

The fundamental contribution of this research is to develop a design framework based on the optimal utilization of IO(Input-Output) resources. It helps designers to create sustainable, accessible, affordable products, regardless of users' socioeconomic status or geographical location, in developed or developing nations. The following are this research's main contributions:

1. Established a universally applicable definition for "frugal design." This definition is critical because it brings clarity and consistency to practitioners, facilitates effective implementation in varied contexts, and forms a solid theoretical basis for researchers, allowing coherent knowledge building. Finally, this emphasizes the foundational change, rather than the traditional notion of 'low-cost innovation'; this research defines frugal design as 'resource-conscious innovation', thereby reinstating its original role as a fundamental unit of the design process.
2. Identifying the core attributes of frugal designs is essential for their practical applications. These attributes allow for structured analysis and measurement, creating a consistent framework for designers and researchers. Because it concentrates on important aspects, i.e., sustainability, functionality, inclusion, and performance, this research provides a clear way to translate theoretical knowledge into tangible designer results. In this context, it highlights how important it is for wider users to have access to frugal design in a variety of socioeconomic and national contexts to ensure a wide range of social impacts.
3. A user experience-based frugal design assessment model (FDEM) with core criteria/attributes (i.e., sustainability, functionality, inclusion, and performance) has been developed. This model provides a comprehensive framework for assessing how products effectively embody frugal design standards. By identifying design flaws and providing implementable knowledge to improve, the designer and organizational model aim to ensure that frugality integrates into the product development process.
4. This research introduces the Frugality Index (FI), a practical tool for assessing the "frugality" of a product, from initial concepts to manufacturing. FI uses a simple 1-5 scale to help designers quickly understand how well their products align with frugal design criteria. This index helps to predict how well the product is adaptable to users and provides clear feedback on where improvement is required.
5. The Frugal Design IO-A framework (input-output analysis) has been introduced to create frugal solutions. This framework provides designers a structured approach to understanding and optimizing the relationship between input and cost throughout

the product lifecycle. In contrast to traditional design methods that can overlook resource limitations and lifecycle effects, frugal design IO-A focuses explicitly on value-maximizing while minimizing resource consumption at every stage. Systematically examining the inputs (materials, energy, Information, space, and time) and outputs (sustainability, Functional, Inclusion, performance) in each stage from raw material sources to end-of-life/disposal. Designers can determine areas for efficiency and resource enhancements. Such a framework is a pragmatic guide that informs designers of key intervention points at which changes may be made to optimize inputs to achieve frugal design outcomes.

6. Addressing manufacturing challenges in resource-related environments requires a balanced approach prioritizing cost-effectiveness and user needs. A simple, frugal design thinking (FDT) conceptual model has been developed. This aims to integrate design thinking principles (DT) and Frugal Design (FD) to create affordable, functional, sustainable, and user-oriented solutions. The FDT model encourages user-centric product development practices by integrating frugal design and design thinking. The model enables marginalized communities by user-led development and allows organizations to construct economically sustainable and profitable business models.

10.3 Limitations of the Work

This research provides valuable insight into frugal design but requires recognizing some limitations. The possible limitations of the current research are expressed as follows:

- The scope of the current research, being rooted in the Indian context, Future studies could enhance applicability by incorporating diverse geographical datasets.
- The frugal design evaluation model in Chapter 4 uses a robust basic structure based on criteria (i.e., sustainability, functionality, inclusion, performance), allowing flexibility for various FD applications adaptation. This adaptability is further improved by the ability of the model to include additional context-specific criteria to ensure relevance and effectiveness in multiple scenarios.
- The proposed input-output analysis (IO-A) model (materials, energy, information, space, time) provides a robust foundation for analyzing Frugal design processes. However, investigating supplementary inputs, i.e., human capital and cultural context, might improve the model's reliability in various application situations.
- The Frugal Design Thinking (FDT) framework proposed in this work has not been thoroughly examined. They were developed based on the relationship between DT and FD attributes.

10.4 Future Directions

- The success of frugal design depends on user acceptance and cultural context. Future research can explore how sociocultural factors influence frugal solutions' perception, implementation, and success, ensuring broader global relevance.
- The frugal design evaluation model (FDEM) could be developed into a robust computational or web-based tool to significantly enhance its utility and accessibility.

- There is a vast scope in the frugal design domain. In particular, exploring its synergy with Industry 4. O technologies (AI, IoT, and digital twins) show great potential for how these technologies might improve predictive maintenance, resource optimization, or user co-creation in frugal solutions, which may lead to new opportunities for scalable innovation.
- Integrating participatory design, crowdsourcing, or community-based innovation methods can enrich a Frugal Design Thinking (FDT) framework, ensuring that frugal solutions are hyper-localized and inclusive.
- The frugal Design IO-A Framework can be extended to include circular economy principles. This allows for the development of frugal products with improved recyclability and material recovery. Future research should examine applications with closed loops in sectors such as electronics and packaging.

Appendix I

Survey Questionnaire: Evaluating a Definition of Frugal Design

Introduction: The survey questionnaire is structured to gather expert feedback on a proposed frugal design definition systematically. The authors focus on establishing a robust and universally applicable frugal design definition. Recognizing the multifaceted nature of this concept and its relevance across various domains, we seek the invaluable insights of experts. Kindly read the proposed definition below and then answer the following questions to the best of your ability. Your responses will be treated with the utmost confidentiality and used solely to improve the definition.

Proposed Definition of Frugal Design: "A resource-conscious innovation paradigm that systematically optimizes the product's inputs (material, energy, information, space, and time) while rigorously maintaining or enhancing function, performance, inclusion, and sustainability."

Expert Background:

Area of Expertise:……………………

Years of Experience in this/related field:…………

Please rate your agreement with the following statements on a scale of 1 to 5, where:

1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree1

Question 1: Comprehensiveness: The proposed definition adequately covers all essential aspects and dimensions of frugal design

Question 2: Completeness: The proposed definition provides a complete and sufficient understanding of frugal design without requiring significant additional explanation

Question 3: Applicability: The proposed definition can be readily applied and understood across various contexts and situations relevant to both emerging and developed markets.

Question 4: Abstractness: The level of abstraction in the proposed definition is appropriate for capturing the essence of frugalism.

Question 5: Consistency: The proposed definition is consistent with existing knowledge, theories, and established understandings related to frugal design

Question 6: Distinguish: The proposed definition clearly distinguishes it from other related concepts or phenomena (i.e., Grassroot innovation, Gandhian innovation, jugaad, cost-efficient innovation)

Overall Feedback: Please provide any additional comments or suggestions you have regarding the proposed definition of frugal design

Appendix II

Questionnaire Survey on Frugal Design Attributes

Aim: The main aim of the survey is to understand the concept of Frugal Design.

Introduction: The main aim of this survey is to understand the concept of Frugal Design and to identify the most relevant attributes that enable a product to achieve frugality. Your responses will help assess how well specific products embody these attributes and contribute to practical, resource-efficient solutions.

Name…………….

Age …………….. Gender: M ☐ F ☐ Other ☐

Qualification: …….
Designation: ………
Department: ………
Work Experience:……
What is your brief job description?
………………………………………………………………

Question 1: Is the Term "Frugal Design/Innovation " known?

YES ☐

NO ☐

How would you define Frugal Design?

……………………………………………………………………………….

Question 2: To what extent are the following prerequisite attributes/features relevant to the following frugal products?

1) Jairpur Foot

2) Lifestraw Water Filter

3)Embrace Warmer

Question 3: Rate the above statements(1 to 39) on the scale of 5 to 1 rating mentioned in the table

5 Most Important,	4 Important	3 Moderately Important	2 Least Important	1 Not Important

1. Sustainability: Avoidance of the depletion of natural resources to maintain an ecological balance
2. Affordability: Having a cost that is not too high
3. Value: The monetary worth of something
4. Environmental: Not harmful to the environment

5. Inclusive: Allowing and accommodating people who have historically been excluded (as because of their race, gender, sexuality, or ability)
6. Scalability: capable of being easily expanded or upgraded on demand
7. Low-cost: Producing or supplying something that is cheap or costs less than usual to buy
8. Accessible: Easy to learn, use, understand, or deal with
9. Simple: Having few parts: not complex or fancy
10. User-centered: Design is focused on the users and their needs.
11. Usability: The quality or state of being usable
12. Utility: The state of being useful, profitable, or beneficial.
13. Minimization: The process of reducing something to the most minor possible level or size
14. Functional: Practical and useful
15. Quality: The standard of something as measured against other things of a similar kind; the degree of excellence of something Utility
16. Socioeconomic: Involving a combination of social and economic factors
17. Recyclability: Able to be recycled
18. Diverse: Composed of distinct or unlike elements or qualities
19. Robustness: The quality of being strong and unlikely to break or fail. Materials were chosen for their robustness and ease of maintenance.
20. Eco-friendly: The product is not harmful to the environment.
21. Adaptability: Capable of being or becoming adapted plants that are easily adaptable to colder climates
22. Viability: The ability to live, grow, and develop
23. Portability: The quality or state of being transferable
24. Performance: The action or process of performing a task or function
25. Durability: Able to exist for a long time without significant deterioration in quality or value
26. Effective: Producing a decided, decisive, or desired effect
27. Appearance: The physical/outward/external appearance of something
28. Applicability: Capable of or suitable for being applied
29. Resource efficient: Using resources in a way that maximizes the output or benefit while minimizing waste and negative impacts
30. Stability: the quality or state of being steady and not changing or being upset in any way
31. Agility: The ability to move quickly and easily
32. Equity: The quality of being fair and impartial.
33. Flexibility: Characterized by a ready capability to adapt to new, different, or changing requirements
34. Safe: Protected from any danger, harm or loss

35. Ergonomic: Designed to make people's working environment more comfortable and to help them work more efficiently
36. Ruggedization: To strengthen (something, such as a machine) for better resistance to wear, stress, and abuse
37. Reproducibility: That can be produced or done again in the same way
38. Reusability: Capable of being used again or repeatedly
39. Standardization: The process of making something conform to a standard

Appendix III

Survey: Evaluating Frugal Products based on Frugal Design Criteria

Aim: This survey evaluates user experiences with frugal products across four critical criteria: performance, functional, sustainability, and inclusivity. By gathering user feedback, the research aims to understand how these products perform in real-world scenarios and how satisfied users are with their overall value and efficiency.

Section 1: General Information

Name: ………………

Gender: …………..

Qualification: ………………………….

Instruction: All participants are requested to choose the product they currently use and rate their experience based on the frugality criteria (sustainability, Functional, Inclusion, and performance) on a 5-point Likert scale.

1: Very Poor, 2: Poor, 3: Average, 4: Good, 5: Excellent

Product Category: Disposable Fast Fashion, Disposable Sanitary Napkins, Tata nano, Husk Power System, eco cooler, Plastic milk packaging, plastic Toothbrush, Disposable razor, Furniture-Plastic chair, Single-Use Paper Cutlery, Tata Swach, Jaipur leg, Embrace global, Keeping Newborns Warm, Logitech- M215, Akash tablet

Section 2

Question 1: Product Usage: How frequently do you use this product?

Answer: First-time, Occasionally, Regularly

1. **Disposable Fast Fashion (Zudio)**

Scenario: Consider buying and wearing inexpensive clothing items frequently available in malls or online.

Sustainability: How would you rate the environmental impact of the clothing (materials, production, disposal)?
Inclusion: How accessible is this fashion for people of different incomes, sizes, and regions?
Functional: How well do these clothes serve your everyday needs (comfort, style, durability)?
Performance: How well do they hold up after repeated washes or daily use?

2. **Disposable Sanitary Pads**

Scenario: Consider using disposable sanitary pads during your menstrual cycle for comfort and protection.
Sustainability: How eco-friendly are these pads in terms of materials and disposal?
Inclusion: How accessible and affordable are they for all socio-economic groups?
Functional: How effectively do they offer protection and ease of use?
Performance: How consistent and reliable is their performance across hours of wear?

3. **Tata Nano**

Scenario: You are driving a Tata Nano car in an Indian urban setting for your daily commute.

Sustainability: How environmentally friendly is the vehicle compared to petrol/diesel alternatives?
Inclusion: How accessible is it in terms of price, infrastructure, and support for diverse users?
Functional: How well does the car meet everyday commuting needs (range, comfort, charging ease)?
Performance: How responsive, reliable, and efficient is it during usage?

4. **Husk Power System**

Scenario: Imagine your village is powered by a mini-grid using rice husk energy.
Sustainability: How renewable and clean is the energy from husk?
Inclusion: How accessible is this power solution for remote or underserved communities?
Functional: How reliably does it supply electricity for household and small-business needs?
Performance: How well does the system perform continuously in various weather and demand conditions?

5. **Eco Cooler**

Scenario: You are using an eco-cooler during peak summer in a non-air-conditioned home.

Sustainability: How eco-friendly is the cooler in terms of water and power consumption?
Inclusion: How affordable and practical is it for middle- and low-income households?
Functional: How effective is it in cooling small rooms?
Performance: How consistent is the airflow and cooling with regular use?

6. **Plastic Milk Packaging**

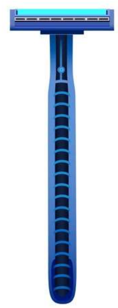
Scenario: You're purchasing milk daily in plastic pouches from local vendors.
Sustainability: How do you rate the impact of plastic packaging on the environment?
Inclusion: How accessible and cost-effective is this form of milk delivery across regions?
Functional: How convenient and safe is the packaging for everyday use?
Performance: How well does it preserve milk and resist leakage/spillage?

7. **Plastic Toothbrush**

Scenario: Consider using a standard toothbrush every morning and night.

Sustainability: How environmentally friendly is the toothbrush you use (plastic)?
Inclusion: Is it available and affordable for users of all demographics?
Functional: How well does it clean your teeth and reach different areas of the mouth?
Performance: How long does it last and remain effective?

8. **Disposable Razor**



Scenario: You use a disposable razor at home for shaving.
Sustainability: How environmentally sustainable is using disposable razors regularly?
Inclusion: Is it an accessible grooming option for all genders and income groups?
Functional: How well does the razor work for clean and safe shaving?
Performance: How many uses can you get out of it before it dulls?

9. **Plastic Chair (Furniture)**

Scenario: You use a plastic chair in your home or at events.
Sustainability: How sustainable is the chair in terms of recyclability and material usage?
Inclusion: How widely available and affordable is it for people across income levels?
Functional: How well does it serve different use cases (indoors/outdoors, weight limits)?
Performance: How long does it last without breaking or cracking?

10. Single-Use Paper Cutlery

Scenario: At a public event or train, you're served food with disposable paper cutlery.
Sustainability: How eco-friendly is the cutlery compared to plastic or reusable options?
Inclusion: Is it an affordable and hygienic option for mass distribution?
Functional: How well does it hold up while eating (strength, shape, absorbency)?
Performance: How clean, safe, and user-friendly is it under typical use?

11. Tata Swach Water Purifier

Scenario: You use this purifier for safe drinking water at home.
Sustainability: Are the components recyclable or long-lasting with minimal waste?
Inclusion: Is it affordable and usable for rural and urban households alike?
Functional: How effectively does it purify water and remove contaminants?
Performance: How durable and consistent is its operation over months?

12. Jaipur Leg

Scenario: A user depends on the prosthetic for everyday mobility.
Sustainability: Are the materials and production environmentally responsible?
Inclusion: Is it accessible for low-income or rural individuals with disabilities?
Functional: How well does it replicate natural movement and support walking?
Performance: How durable, adjustable, and comfortable is it over time?

13. Embrace Global – Infant Warmer

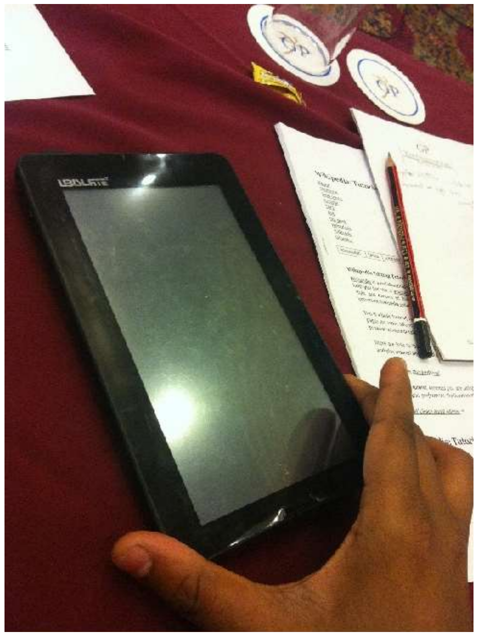
Scenario: Used in a health clinic to keep premature babies warm.
Sustainability: Is the warmer reusable and low-energy?
Inclusion: Is it accessible for clinics without incubators or in rural areas?
Functional: How effectively does it regulate infant temperature?
Performance: How reliable is it in daily clinical operations?

14. Logitech M215 Mouse

Scenario: You're using the wireless mouse at school, home, or office.
Sustainability: Is it energy-efficient and made with recyclable parts?

Inclusion: Is it reasonably priced and easy for people to use regardless of age or ability?
Functional: How well does it track and click for daily computing tasks?
Performance: How reliable is it in terms of connectivity, battery life, and responsiveness?

15. Aakash Tablet



Scenario: Used by students in a government school to access digital learning materials.
Sustainability: How long-lasting and energy-efficient is the device?
Inclusion: How effectively does it support students in low-income or rural communities?
Functional: How well does it support educational apps, internet, and multimedia?
Performance: How reliable is the tablet in terms of speed, battery, and durability?

Appendix IV

A Survey Questionnaire

Aim: This survey is intended to assess resource efficiency throughout a product's lifecycle. The goals are to find chances for resource minimization/optimization and identify underlying root causes impeding the achievement of product frugality.

Product Information: sanatory napkins (Paree) and fast fashion (Zudio)

Instruction: Evaluate the product across its five lifecycle stages (Sourcing, Manufacturing, Transportation, Use, and End-of-Life), focusing on how efficiently keys are utilized. Identify where resource optimization is lacking and suggest possible reasons for these inefficiencies. The goal is to help uncover the root causes that prevented the product from meeting frugality criteria, such as sustainability, functional, performance, and inclusion. Use your expertise to provide thoughtful, concise insights into both surface-level issues and deeper systemic problems.

Stage 1: Sourcing of material

1. What criteria do you use for selecting materials (e.g., cost, sustainability)?
2. How do you minimize material waste during sourcing?
3. Do you source materials locally?
4. What measures do you take to ensure energy efficiency in sourcing?
5. How do you track and manage energy consumption in material sourcing and transportation?
6. Do you use renewable energy sources in sourcing or transportation?
7. How do you use data to make sourcing decisions?
8. Do you have integrated systems for real-time information on material availability
9. How do you optimize storage space for materials?
10. How do you optimize transportation routes and methods to reduce space usage and costs?
11. How do you manage lead times to ensure timely delivery without excessive inventory?

Stage 2: Manufacturing/Production

1. How do you minimize material waste during manufacturing?
2. Are there systems in place to track material usage and waste?
3. What measures do you take to ensure energy efficiency in manufacturing?
4. How do you track and manage energy consumption in the manufacturing process?
5. Do you use renewable energy sources in manufacturing?
6. How do you use information to optimize manufacturing processes?
7. Are your manufacturing processes guided by real-time data?

8. How do you optimize the use of floor space in your manufacturing facilities?
9. How do you manage the storage of raw materials and finished products to maximize space utilization?
10. How do you streamline production processes to minimize downtime?
11. What steps do you take to ensure timely completion of manufacturing tasks?
12. How do you manage production schedules to balance efficiency and flexibility?

Stage 3: Transportation

1. How do you minimize packaging material while ensuring product safety?
2. Are your packaging materials recyclable or made from recycled content?
3. How do you track and manage packaging waste during distribution?
4. What measures do you take to ensure energy efficiency in transportation?
5. How do you track and manage fuel consumption during distribution?
6. Do you use energy-efficient or alternative fuel vehicles in your transportation fleet?
7. How do you use information to optimize transportation routes and schedules?
8. How is information about fuel consumption, delivery times, and costs collected and analyzed?
9. Do you use real-time tracking systems for monitoring shipments?
10. How do you optimize the loading and unloading processes to maximize space utilization?
11. Are there practices in place to reduce unused space in transport vehicles?
12. How do you manage warehouse space for storing goods before distribution?
13. How do you ensure timely delivery of products to minimize delays?
14. What steps do you take to streamline loading and unloading times?
15. How do you manage delivery schedules to balance efficiency and customer satisfaction?

Stage 4: Use

1. Do you feel that the amount of material used in the product is appropriate for its function, or could it be reduced?
2. Have you noticed any parts of the product that seem overbuilt or unnecessarily bulky?
3. Are you aware of which parts of the product can be recycled? Is this information clear and accessible?
4. Did you find the packaging materials excessive or wasteful? Would you prefer more sustainable or minimal packaging?
5. Do the instructions and information provided with the product help you use it efficiently? Is there any missing information that would improve your experience?
6. Does the product provide useful feedback during its use? How could this feedback be improved?
7. How would you rate the product's energy consumption during use? Have you noticed any unnecessary energy usage?

8. Are there energy-saving features in the product that you find useful? Are there any other energy efficiencies you would like to see?"
9. Does the product fit well within the space you have designated for it? Does it require more space than expected?
10. Is the product easy to move or store when not in use? How could its design be improved to save space?"
11. How long does it take to set up and start using the product? Are there any steps that seem to take too long?"
12. Does the product help you complete tasks faster than you could without it? Where do you think time could be saved in its operation?

Stage 5: End of life/ Decline

1. How easy is it to recycle or properly dispose of the product? Are there components that you found challenging to recycle?
2. Are there any parts of the product that could be reused or repurposed after its primary use is over?
3. Have you considered the amount of waste generated when discarding the product? What could be done to minimize this waste?
4. Were the instructions on how to dispose of or recycle the product clear and easy to follow
5. Did you receive any information on how to repurpose or extend the product's life?
6. Did the disposal or recycling of the product require any energy-intensive processes?
7. Was disassembling the product into smaller components easy for easier recycling or disposal?
8. How long did it take to disassemble the product for disposal or recycling?
9. Was the process of disposing of or recycling the product time-efficient?

Appendix V

Survey on the Input-Output Relationship of the Frugal Design Framework

Introduction: Frugal design aims to create products that are accessible, resource efficient, and high-performing while addressing sustainability and inclusion. A key aspect of frugal design is how effectively core input resources (Material, Energy, Information, Space, and Time) are utilized to achieve desired outcomes (Sustainability, Inclusion, Functional, and Performance).

This survey is designed to understand your perspectives and experiences regarding the relationship between these input variables and output elements in frugal design. Your responses will contribute to developing better frameworks and tools to support designers and organizations in creating more frugal and inclusive products.

Section 1: Demographics

Name (Optional):………….

Profession/Role: ……………..

Years of experience: ……………….

Industry/Sector: …………….

Section 2: Perceived Influence of Inputs on Outputs

Instructions: On a scale of 1 to 5, rate how strongly you believe each input influences the following output dimensions of frugal design.

Scale: 1 = Not at all, 2 = Slightly, 3 = Moderately, 4 = Strongly, 5 = Very strongly

	Sustainability	Inclusion	Functional	Performance
Material (e.g., reuse, recyclability)	1☐, 2 ☐, 3 ☐ 4☐,5 ☐	1☐, 2 ☐, 3 ☐ 4☐,5 ☐	1☐, 2 ☐, 3 ☐ 4☐,5 ☐	1☐, 2 ☐, 3 ☐ 4☐,5 ☐
Energy (used in making or using)	1☐, 2 ☐, 3 ☐ 4☐,5 ☐	1☐, 2 ☐, 3 ☐ 4☐,5 ☐	1☐, 2 ☐, 3 ☐ 4☐,5 ☐	1☐, 2 ☐, 3 ☐ 4☐,5 ☐
Information (data, knowledge used	1☐, 2 ☐, 3 ☐ 4☐,5 ☐	1☐, 2 ☐, 3 ☐ 4☐,5 ☐	1☐, 2 ☐, 3 ☐ 4☐,5 ☐	1☐, 2 ☐, 3 ☐ 4☐,5 ☐
Space (physical or spatial efficiency	1☐, 2 ☐, 3 ☐ 4☐,5 ☐	1☐, 2 ☐, 3 ☐ 4☐,5 ☐	1☐, 2 ☐, 3 ☐ 4☐,5 ☐	1☐, 2 ☐, 3 ☐ 4☐,5 ☐
Time (to make, use, maintain)	1☐, 2 ☐, 3 ☐ 4☐,5 ☐	1☐, 2 ☐, 3 ☐ 4☐,5 ☐	1☐, 2 ☐, 3 ☐ 4☐,5 ☐	1☐, 2 ☐, 3 ☐ 4☐,5 ☐

Section 3: Specific Reflections on Input-Output Relations

Q 1: What challenges have you faced in aligning inputs (resources) with desired frugal design outputs?

Q2: What recommendations would you give to improve the input-output balance in frugal product design?

Appendix VI

Survey questionnaire for validating the input-output Frugal Design Framework

Aim: This survey evaluates the application of the input-output frugal design framework. Frugal design focuses on maximizing value while minimizing resource consumption. Your expert opinion is invaluable in helping us understand how this model is applied in real-world projects. The survey consists of scenario-based questions related to five case studies.

Instruction: Kindly answer the questions thoughtfully and to the best of your ability. Your responses will be kept confidential and used for research purposes only. You are requested to answer on a 5-point Likert scale.

Likert Scale - 1 to 5, 1=Strongly Disagree, 5=Strongly Agree)

Section 1

Name:…………

Occupation/Designation:…………..

Experience:…………..

Section 2: Case Research Evaluations

Case 1: Modular Pre-fabricated Housing

This case research examines a modular, pre-fabricated home design that uses recycled and locally sourced materials. The homes are designed for rapid assembly and aim to be affordable and energy-efficient."

Input

- Material: Using standardized and locally available materials reduced costs and waste.
- Energy: Energy consumption was minimized during prefabrication and installation.
- Space: The housing design efficiently used available land and layout.
- Time: Construction time was significantly reduced due to modular assembly.
- Information: Digital tools (e.g., CAD/BIM) improved accuracy and design efficiency.

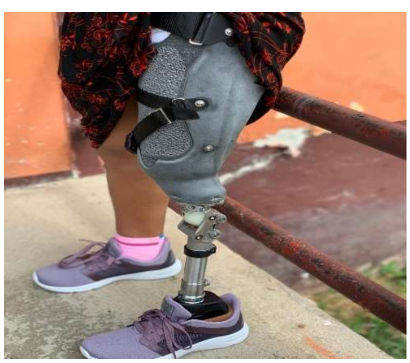
Output

- Sustainability: The housing system promotes environmental and economic sustainability.
- Inclusion: The design is affordable and accessible to lower-income households.
- Functionality: The housing meets essential living requirements efficiently.
- Performance: The housing performs well in terms of durability, insulation, and user comfort.

Open-Ended Questions:

- "What are the key strengths of this case research in relation to frugal design framework?"
- What are the key weaknesses or areas for improvement in this case research from a frugal design perspective?"
- Are there any other factors not captured by the Likert scales that you think are important to consider when evaluating this case research?

Case 2: 3D-Printed Prosthetics



Scenario: Customized prosthetics are created using 3D printing with open-source designs and low-cost materials.

Input:

- Material: Low-cost and lightweight materials were used without compromising usability.
- Energy: The 3D printing process used minimal energy compared to traditional manufacturing.
- Space: The prosthetics are designed to be ergonomic and compact for user comfort.
- Time: Prosthetics were produced and delivered quickly through rapid manufacturing.
- Information: Open-source designs and user data enabled customization.

Outputs:

- Sustainability: Local production and material choice reduced the environmental footprint.
- Inclusion: The prosthetics are accessible to users across economic and physical needs.
- Functionality: They provide essential mobility and usability for daily tasks.
- Performance: The prosthetics are reliable, comfortable, and adjustable over time.

Open-Ended Questions:

- "What are the key strengths of this case research in relation to frugal design framework?"
- What are the key weaknesses or areas for improvement in this case research from a frugal design perspective?"
- Are there any other factors not captured by the Likert scales that you think are important to consider when evaluating this case research?

Case 3: Vertical Gardening

Scenario: Food is grown using vertical gardening systems made from reused materials and low-energy technologies in limited urban spaces.

Input

- Material: Recycled or locally sourced materials were used in the garden structure.

- Energy: The garden uses low-energy watering and lighting systems.
- Space: The vertical design effectively utilizes small or unused spaces.
- Time: Time required for installation and maintenance is minimal.
- Information: Knowledge from communities and manuals supports better gardening practices.

Output

- Sustainability: The system contributes to local food production with minimal resources.
- Inclusion: The garden is suitable for low-income, urban populations with limited land.
- Functionality: The system supports diverse plant growth and easy maintenance.
- Performance: The garden performs well in different urban settings and seasons.

Open-Ended Questions:

- "What are the key strengths of this case research about frugal design framework?"
- What are the key weaknesses or areas for improvement in this case research from a frugal design perspective?"
- Are there any other factors not captured by the Likert scales that are important to consider when evaluating this case research?

Case 4: Aeroplane

Scenario: A commercial aircraft is designed using lightweight composites, modular interiors, and smart systems for reduced fuel use and better performance.

Input

- Material: Use of lightweight, durable materials reduced the weight and fuel cost.
- Energy: Energy-efficient engines and systems reduced operational consumption.
- Space: Cabin space is modular, adaptable for different layouts and uses.
- Time: The Time required for maintenance and reconfiguration is minimized.

- Information: Real-time data and intelligent systems optimize performance and safety.

Output

- Sustainability: The aircraft design reduces long-term environmental impact.
- Inclusion: Modular interiors make the plane adaptable for diverse user needs.
- Functionality: The aircraft supports cargo, passenger, and flexible operations.
- Performance: The aircraft exhibits high efficiency, reliability, and safety.

Open-Ended Questions:

- "What are the key strengths of this case research in relation to frugal design framework?"
- What are the key weaknesses or areas for improvement in this case research from a frugal design perspective?"
- Are there any other factors not captured by the Likert scales that you think are important to consider when evaluating this case research?

Case 5: Modular Furniture

Scenario: Flat-pack modular furniture made from repurposed wood and open-source designs, designed for easy transport and assembly.

Input

- Material: Reclaimed or eco-certified materials were effectively used in production.
- Energy: The production and assembly processes consume minimal energy.
- Space: Modular design maximizes usability in small living areas.
- Time: Furniture is quick to assemble, disassemble, and relocate.
- Information: Open-source instructions make it easy for users to build and customize.

Output

- Sustainability: The furniture is long-lasting, repairable, and recyclable.
- Inclusion: It is affordable and usable by people in diverse living conditions.
- Functionality: The furniture serves multiple functions in a limited space.
- Performance: It performs well in terms of durability, ease of use, and adaptability.

Open-Ended Questions:

- "What are the key strengths of this case research in relation to frugal design framework?"
- What are the key weaknesses or areas for improvement in this case research from a frugal design perspective?"
- Are there any other factors not captured by the Likert scales that you think are important to consider when evaluating this case research?

Appendix VII

Survey: Evaluating Products based on Frugal Design Thinking (FDT) Framework

Aim: This survey evaluates user experiences with five products across four key attributes of FDT: sustainable user-centric design, functional problem framing, inclusive iterative process, and rational performance design. By gathering user feedback, we aim to understand how these products perform in real-world scenarios and how satisfied users are with their overall value and efficiency.

Section 1: General Information
Name: ……………………
Gender: …………………
Organization:……………..
Designation/role…………..

Product Category: GE, ECG, Fitbit wearables, IKEA flat back furniture, Oxo Good Grip kitchen tools, Remotion Knees

Instruction: All participants are requested to read the scenario for the product you use and rate your experience based on the following attributes using a 5-point Likert scale:
1 = Needs Improvement, 2 = Satisfactory, 3 = Excellent

Section 2
Q 1: Product Usage: How frequently do you use this product?
Answer: First-time, Occasionally, Regularly

Section 3
Product 1: GE ECG Machine

Scenario:
You are operating a General Electric ECG machine in a healthcare setting to monitor a patient's heart activity. The device is designed to be compact, energy-efficient, and easy to transport between rooms or facilities, making it suitable for diverse healthcare contexts, from urban hospitals to rural clinics.
Q1: Sustainable User-Centric Design – How well does the product integrate environmental sustainability (e.g., energy efficiency, material use) with ease of use for healthcare professionals and patient comfort?
Q2: Functional Problem Framing – How effectively does the product address

the challenge of accurate, timely heart monitoring in your healthcare setting?
Q3: Inclusive Iterative Process – How adaptable and inclusive is the product for different healthcare environments and diverse patient populations?
Q4: Rational Performance Design – How reliably does the product perform in terms of measurement accuracy, durability, and operational efficiency?

Product 2: Fitbit Wearables

Scenario:
You are using a Fitbit wearable device to track daily activity, heart rate, and sleep quality. The product is designed to integrate seamlessly into daily life, providing data for personal health goals, fitness tracking, and lifestyle improvement.

Q1: Sustainable User-Centric Design – How effectively does the Fitbit balance sustainability (battery life, materials) with comfort, ease of use, and data accessibility?
Q2: Functional Problem Framing – How well does the Fitbit meet your needs for activity tracking, health monitoring, and goal setting in your context?
Q3: Inclusive Iterative Process – How inclusive is Fitbit's design in accommodating different user groups (e.g., various fitness levels, ages, and accessibility needs)?
Q4: Rational Performance Design – How reliably does the Fitbit perform in terms of accuracy, durability, and integration with apps or platforms?

Product 3: IKEA Flat-Pack Furniture

Scenario:

You have purchased an IKEA flat-pack furniture item (e.g., table, wardrobe, shelf) for your home or workplace. The product is designed to be affordable, easy to transport, and assembled by the user using the provided instructions and tools.

Q1: Sustainable User-Centric Design – How effectively does the furniture integrate sustainability (renewable materials, efficient transport) with user-friendliness and assembly experience?

Q2: Functional Problem Framing – How well does the furniture meet your functional needs for space utilization, storage, or décor in your context?

Q3: Inclusive Iterative Process – How inclusive is the product design for users with varying skill levels, physical abilities, and living situations?

Q4: Rational Performance Design – How reliably does the furniture perform over time in terms of stability, durability, and functionality?

Product 4: Oxo Good Grips Kitchen Tools

Scenario:

You are using an Oxo Good Grips kitchen tool (e.g., peeler, can opener, whisk) designed with ergonomic handles and a comfortable grip, originally created for people with arthritis but suitable for all users.

Q1: Sustainable User-Centric Design – How effectively does the kitchen tool integrate sustainability (material use, durability) with ease of handling and comfort?
Q2: Functional Problem Framing – How well does the tool address the core functional needs of your cooking or food preparation tasks?
Q3: Inclusive Iterative Process – How inclusive is the design for users with different physical abilities, hand sizes, and cooking experience levels?
Q4: Rational Performance Design – How reliably does the tool perform in terms of efficiency, precision, and comfort during use?

Product 5: ReMotion Knee

Scenario:

You are using a ReMotion Knee prosthetic in your daily life for mobility. Designed specifically for affordability and functionality, the prosthetic is durable and suited for various environments, particularly in low-resource settings.
Q1: Sustainable User-Centric Design – How well does the prosthetic integrate sustainability (material choice, lifespan) with comfort and usability for the wearer?
Q2: Functional Problem Framing – How effectively does it meet your mobility needs in daily activities and specific environments?
Q3: Inclusive Iterative Process – How inclusive was the product development in considering diverse user needs (age, activity level, cultural context)?
Q4: Rational Performance Design – How reliably does it perform in terms of comfort, adaptability, and long-term use?

References

A. Brem, C. Wimschneider, A. R. de Aguiar Dutra, A. L. V. Cubas, and R. D. Ribeiro,"How to design and construct an innovative frugal product? An empirical examination of a frugal new product development process," Journal of Cleaner Production 275, p. 122232, 2020

A. Habibi, A. Sarafrazi, and S. Izadyar, "Delphi technique theoretical framework in qualitative research," The International Journal of Engineering and Science, 3(4), pp.8-13,2014.

A. Joshi, S. Kale, S. Chandel, and D. K. Pal. "Likert scale: Explored and explained," British journal of applied science and technology 7(4),pp, 396,2015.

Abdi, H., Guillemot, V., Eslami, A., and Beaton, D. (2018). Canonical Correlation Analysis.

Abichandani, Y. (2014). Jugaad innovation: think frugal, be flexible, generate breakthrough growth. *European Journal of Training and Development*, *38*(7), 689-691.

Agarwal, N., and Brem, A. (2012, June). Frugal and reverse innovation-Literature overview and case research insights from a German MNC in India and China. In *2012 18th international ICE conference on engineering, technology and innovation* (pp. 1-11). IEEE.

Agarwal, N., and Brem, A. (2017). Frugal innovation-past, present, and future. *IEEE Engineering Management Review*, *45*(3), 37-41.

Agarwal, S., and Sharma, S. N. (2014). Universal Design to Ensure Equitable Society. *International Journal of Engineering and Technical Research (IJETR)*, *1*.

Agnihotri, A. (2015). Low-cost innovation in emerging markets. *Journal of Strategic Marketing*, *23*(5), 399-411.Albert M. Sustainable frugal innovation - The connection between frugal innovation and sustainability. *J Clean Prod* 2019;237:117747.

Ahuja, S. (2014). Cost vs. value+ empathy: a new formula for frugal science. *Design Management Review*, *25*(2), 52-55.

Al-Aomar, R. (2010). A combined ahp-entropy method for deriving subjective and objective criteria weights. *The International Journal of Industrial Engineering: Theory, Applications and Practice*, *17*(1), 12-24.

Albert, M. (2019). Sustainable frugal innovation-The connection between frugal innovation and sustainability. *Journal of Cleaner Production*, *237*, 117747.

Alwania, K. H. M. (2024). Iraqi Journal of Civil Engineering.

Al-Zwainy, F. M. S., Abdulmajeed, M. H., & Aljumaily, H. S. M. (2013). Using multivariable linear regression technique for modeling productivity construction in Iraq. *Open Journal of Civil Engineering*, *3*(3), 127-135.

Amanatidou, E., and Gritzas, G. (2020). Innovation for Social Needs. In *Responsibility Beyond Growth* (pp. 75-90). Bristol University Press.

Angot, J., and Plé, L. (2015). Serving poor people in rich countries: the bottom-of-the-pyramid business model solution. *Journal of Business Strategy*, *36*(2), 3-15.

Apple warns of lower iphone shipments as COVID curbs hobble China plant | Reuters. (n.d.). https://www.reuters.com/technology/foxconn-revises-down-q4-outlook-zhengzhou-covid-woes-2022-11-06/

Archer, B. (1979). Design as a discipline. *Design studies*, *1*(1), 17-20.

Argandoña, A. (2010). Frugality.

Arshad, H., Radić, M., and Radić, D. (2018). Patterns of frugal innovation in healthcare. *Technology Innovation Management Review*, *8*(4).

Arya, A. P., and Klenerman, L. (2008). The jaipur foot. *The Journal of Bone and Joint Surgery British Volume*, *90*(11), 1414-1421.

Ashfaq, F., Waseer, W. A., and Ilyas, S. (2018). Frugal Innovation–Its Concept & Attributes of Success; Learning Lessons for Western MNCs. *International Journal of Management Sciences and Business Research*, *1*, 49-54.

Ashour, M., and Mahdiyar, A. (2024). A comprehensive state-of-the-art survey on the recent modified and hybrid analytic hierarchy process approaches. *Applied Soft Computing*, *150*, 111014.

Balka, K., Raasch, C., and Herstatt, C. (2014). The effect of selective openness on value creation in user innovation communities. *Journal of Product Innovation Management*, *31*(2), 392-407.

Barclay, C. (2014). Using frugal innovations to support cybercrime legislations in small developing states: introducing the cyber-legislation development and implementation process model (CyberLeg-DPM). *Information Technology for Development*, *20*(2), 165-195.

Barnett, M., and Deschamps, J. P. (2005). Logitech: Learning from customers to design a new product. *case IMD*, (5-0679), 5.

Barnikol, J. (2024). Green and competitive: who influences the development of advanced frugal product characteristics?. *Technology Analysis and Strategic Management*, 1-14.

Barsalou, M. (2023). Criteria for the prioritization of hypotheses in root cause analysis. *Quality and Reliability Engineering International*, *39*(1), 132-142.

Basu, R. R., Banerjee, P. M., and Sweeny, E. G. (2013). Frugal innovation: core competencies to address global sustainability. *Journal of Management for Global sustainability*, *1*(2), 5.

Beckman, S. L., and Barry, M. (2007). Innovation as a learning process: Embedding design thinking. *California management review*, *50*(1), 25-56, doi: 10.2307/41166415

Bencsik, A., Machova, R., and Tóth, Z. (2016). Cheap and clever–symbiosis of frugal innovation and knowledge management. *Problems and Perspectives in Management*, *14*(1), 85-93.

Benyon, D. (2019). *Designing user experience*. Pearson UK.

Benyus, J. M. (1997). Biomimicry: Innovation inspired by nature.

Bertero, V. V. (1996), June. State of the art report on: design criteria. In *Proceedings of 11th world conference on earthquake engineering, Acapulco, Mexico, Oxford, Pergamon*.

Beverland, M. B., Wilner, S. J., and Micheli, P., (2015). Reconciling the tension between consistency and relevance: design thinking as a mechanism for brand ambidexterity. *Journal of the Academy of Marketing Science*, *43*, 589-609, doi: 10.1007/s11747-015-0443-8.

Bevolo, M. (2022, January 5). Bruce Mau talks: from life-centered design, to events for preferable futures. *Medium*. https://marco-bevolo.medium.com/bruce-mau-talks-from-life-centered-design-to-events-for-preferable-futures-3dae98f6e3cf 2015;36:3–15.

Bhattacharjya, B. R., Bhaduri, S., & Kakoty, S. K. (2023). Co-creating community-led frugal innovation: An adapted Quadruple Helix?. *Technovation*, *124*, 102752.

Bhatti, Y. A., and Ventresca, M. (2013). How can 'frugal innovation'be conceptualized?. *Available at SSRN 2203552*.

Bhatti, Y., and Prabhu, J. (2019). Frugal innovation and social innovation: Linked paths to achieving inclusion sustainably. *Handbook of inclusive innovation*, 354-376.

Bhatti, Y., Basu, R. R., Barron, D., and Ventresca, M. J. (2018). *Frugal innovation: Models, means, methods*. Cambridge University Press.

Bhatti, Y., Khilji, S. E., and Basu, R. (2013). Frugal innovation. In *Globalization, change and learning in South Asia* (pp. 123-145). Chandos Publishing. 10.1533/9780857094650

Binswanger, M. (2001). Technological progress and sustainable development: what about the rebound effect?. *Ecological economics*, *36*(1), 119-132.

Bloomberg. (2019, July 12). The world's 2-billion-ton trash problem just got more alarming. *The Economic Times*. https://economictimes.indiatimes.com/news/international/world-news/the-worlds-2-billion-ton-trash-problem-just-got-more-alarming/articleshow/70186945.cms?from=mdr

Bongaarts, J. (2009). Human population growth and the demographic transition. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1532), 2985-2990.

Bostrom, M. (2023). *The social life of unsustainable mass consumption*. Rowman & Littlefield.

Bouckaert, L., and Zsolnai, L. (2012). Spirituality and business: An interdisciplinary overview. *Society and Economy*, *34*(3), 489-514.

Bouckaert, L.; H. Opdebeeck; L. Zsolnai (2011). Frugality. In: Bouckaert, L.; L. Zsolnai (Eds). Handbook of Spirituality and Business. London: Palgrave Macmillan.

Bound, K., and Thornton, I. W. (2012). Our frugal future: Lessons from India's innovation system.

Brem, A., & Wolfram, P. (2014). Research and development from the bottom up-introduction of terminologies for new product development in emerging markets. *Journal of Innovation and Entrepreneurship*, *3*, 1-22.

Brem, A., and Ivens, B. (2013). Do frugal and reverse innovation foster sustainability? Introduction of a conceptual framework. *Journal of Technology Management for Growing Economies*, *4*(2), 31-50.

Brem, A., Wimschneider, C., de Aguiar Dutra, A. R., Cubas, A. L. V., and Ribeiro, R. D. (2020). How to design and construct an innovative frugal product? An empirical examination of a frugal new product development process. *Journal of Cleaner Production*, *275*, 122232.

Brezet,H. and Van Hemel,C. (1997), "Ecodesign, A Promising Approach*", Uni. Nat. Pub., Paris*.

Broadbent, J. (2002). Design and sociocultural evolution: Theoretical and practical considerations. *World Futures: The Journal of General Evolution*, *58*(2-3), 213-228.

Brown, T. (2008). Design thinking. *Harvard business review*, *86*(6), 84.

Buchanan, R. (2019). Systems thinking and design thinking: The search for principles in the world we are making. *She Ji: The Journal of Design, Economics, and Innovation*, *5*(2), 85-104, doi: 10.1016/j.sheji.2019.04.001.

C. H. Lawshe, "A quantitative approach to content validity," Personnel psychology, 28(4), 563-575. 1975.

C. Horn, and B. Alexander. "Strategic directions on innovation management–a conceptual framework," Management research review, *36*(10), pp.939-954.2013.

C.K. Prahalad and R.A. Mashelkar, "Innovation's holy grail", *Harv. Bus. Revi.* Vol. *88*, no. 7/8, pp.132-141,2010.

C.M. Patinoand, , J.C. Ferreira, " Inclusion and exclusion criteria in research studies: definitions and why they matter," Jornal Brasileiro de Pneumologia, 44, pp.84-84,2018.

Cai, Q., Ying, Y., Liu, Y., and Wu, W. (2019). Innovating with limited resources: The antecedents and consequences of frugal innovation. *Sustainability*, *11*(20), 5789.

Cankaya, S., Balkaya, A., and Karaagac, O. (2010). Canonical correlation analysis for the determination of relationships between plant characters and yield components in red pepper (Capsicum annuum L. var. conoides (Mill.) Irish) genotypes. *Spanish Journal of Agricultural Research*, *8*(1), 67-73.

Card, A. J., Ward, J., and Clarkson, P. J. (2012). Successful risk assessment may not always lead to successful risk control: a systematic literature review of risk control after root cause analysis. *Journal of Healthcare risk management*, *31*(3), 6-12.

Carr, S. D., Halliday, A., King, A. C., Liedtka, J., and Lockwood, T. (2010). The influence of design thinking in business: Some preliminary observations. *Design Management Review*, *21*(3), 58-63.

Carroll, J. M. (1997). Scenario-based design. In *Handbook of human-computer interaction* (pp. 383-406). North-Holland.

Ceri, C. N. (2013). *Design analysis of the four-bar Jaipur-Stanford prosthetic knee for Developing countries* (Doctoral dissertation, Massachusetts Institute of Technology).

Charmaz, K. (2006). *Constructing grounded theory: A practical guide through qualitative analysis*. sage.

Chen, S. H., Wen, P. C., & Tai, C. Y. (2013). China's good-enough innovation: Shanzhai Handsets and Shanzhai economy. In *The economic geography of the IT industry in the Asia Pacific region* (pp. 169-188). Routledge.

Chikweche, T. (2013). Revisiting the business environment at the bottom of the pyramid (bop)—from theoretical considerations to practical realities. *Journal of Global Marketing*, *26*(5), 239-257.

Child, S., and Shaw, S. (2023). A Conceptual Approach to Validating Competence Frameworks. *Research Matters*, *35*, 27-40.

Clouting, L. (2018). 8 Facts about Clothes Rationing in Britain During the Second World War. *Imperial War Museum*.

Collier, D., and Mahon, J. E. (1993). Conceptual "stretching" revisited: Adapting categories in comparative analysis. *American Political Science Review*, *87*(4), 845-855.

Connelly, L. M. (2011). Cronbach's alpha. *Medsurg nursing*, *20*(1), 45-47.

Corbin, J. M., and Strauss, A. (1990). Grounded theory research: Procedures, canons, and evaluative criteria. *Qualitative sociology*, *13*(1), 3-21.

Côrte-Real, E. (2010). The Word' Design': Early Modern English Dictionaries and Literature on Design, 1604–1837. *Working Papers on Design*, *4*(5), 1-15.

Coşkun, R., Akande, A., and Renger, R. (2012). Using root cause analysis for evaluating program improvement. *Evaluation Journal of Australasia*, *12*(2), 4-14.

Council, D. (2019). Design council. *September|{,}{| Ö. https://www. designcouncil. org. uk/news-opinion/what-framework-innovationdesign-councils-evolved-double-diamond*

Cunha, M. P. E., Rego, A., Oliveira, P., Rosado, P., and Habib, N. (2014). Product innovation in resource-poor environments: Three research streams. *Journal of Product Innovation Management*, *31*(2), 202-210.

D. Roiland, "Frugality, a positive principle to promote sustainable development," Journal of Agricultural and Environmental Ethics, 29: 571-585, 2016.

D.E. Rossetto, F.M. Borini, R.C. Bernardes and G.L. Frankwick., "Measuring frugal innovation capabilities: An initial scale proposition," Technovation, 121, p.102674.2023

Da Silva, R. H., Kaminski, P. C., and Armellini, F., (2020). Improving new product development innovation effectiveness by using problem solving tools during the conceptual development phase: Integrating Design Thinking and TRIZ. *Creativity and Innovation Management*, *29*(4), 685-700, doi: 10.1111/caim.12399.

Dabić, M., Obradović, T., Vlačić, B., Sahasranamam, S., & Paul, J. (2022). Frugal innovations: A multidisciplinary review & agenda for future research. *Journal of Business Research*, *142*, 914-929.

Dan, P. K., Tiwari, T., & Basu, P. (2022, November). Fuzzy front end and design thinking integrated frugal innovation framework for feature concept generation in a product: Portrayal for a wheelchair. In *Interdisciplinary Conference on Innovation, Desgin, Entrepreneurship, And Sustainable Systems* (pp. 301-316). Cham: Springer International Publishing.

Das, K., Dutta, P., and Gogoi, J. (2021). 'Foldscope'-A simple and economical microscope. *Journal of Biological Education*, *55*(2), 217-222.

Das, R., Jana, N., Arora, N., and Sengupta, S. (2020). Ultrasound assessment of fetal hearing response to vibroacoustic stimulation. *The Journal of Maternal-Fetal and Neonatal Medicine*, *33*(14), 2326-2332.

Davidson, L. (2015). Do frugal innovations lead to frugal outcomes? A case research of healthcare in India. *Wharton Research Scholars thesis. Available* *at: http://repository. upenn. edu/wharton_ research_scholars/127/(accessed on 18 April 2017)*.

De Pauw, I., Kandachar, P., Karana, E., Peck, D., and Wever, R. (2010, October). Nature inspired Design: Strategies towards sustainability. In *Knowledge Collaboration & Learning for Sustainable Innovation: 14th European Roundtable on Sustainable Consumption and Production (ERSCP) conference and the 6th Environmental Management for Sustainable Universities (EMSU) conference, Delft, The Netherlands, October 25-29, 2010*. Delft University of Technology; The Hague University of Applied Sciences; TNO.

De Waal, G. A. (2016). An extended conceptual framework for product-market innovation. *International Journal of Innovation Management*, *20*(05), 1640008.

De Young, R. (1985). Encouraging environmentally appropriate behavior: The role of intrinsic motivation.

Desa, U. N. (2008). World population prospects.

Desa, U. N. (2019). United Nations Department of economic and social affairs. *Population Division. World Population Prospects*.

Desmet, P. M., and Pohlmeyer, A. E. (2013). Positive Design: An introduction to design for subjective well-being. *International journal of design*, *7*(3).

Dictionary, O. E. (2020). 6 Context, Context, Context. *We Are Not Users: Dialogues, Diversity, and Design*, 101.

Direction, S. (2016). Creating value through innovation: how SMEs can compete. *Strategic Direction*, *31*(9), 35-37.

Doggett, A. M. (2005). Root cause analysis: a framework for tool selection. *Quality Management Journal*, *12*(4), 34-45.

Dominoni, A.(2024). Design for Sustainability and Inclusion in Space.

Dos Santos, S. F., and Brandi, H. S. (2014). A canonical correlation analysis of the relationship between sustainability and competitiveness. *Clean Technologies and Environmental Policy*, *16*, 1735-1746.

Doucet, S. M., & Meadows, M. G. (2009). Iridescence: a functional perspective. *Journal of the Royal Society Interface*, *6*(suppl_2), S115-S132.

Drisko, J. W., and Maschi, T. (2016). Content analysis. *Oxford University Press*, USA.

Duflou, J. R., Sutherland, J. W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S., ... and Kellens, K. (2012). Towards energy and resource efficient manufacturing: A processes and systems approach. *CIRP annals*, *61*(2), 587-609.

Elsbach, K. D., and Stigliani, I., (2018). Design thinking and organizational culture: A review and framework for future research. *Journal of Management*, *44*(6), 2274-2306, doi: 10.1177/0149206317744252.

Escudero-Cipriani, C., García-del Junco, J., Chafloque-Céspedes, R., and Alvarez-Risco, A. (2024). Frugal innovation in the business environment: a literature review and future perspectives. *Frontiers in Artificial Intelligence*, *7*, 1385522.

F. Yaghmaie, "Content validity and its estimation," Journal of medical education, 3(1), 2003.

Farooq, R. (2017). A conceptual model of frugal innovation: is environmental munificence a missing link?. *International Journal of Innovation Science*, *9*(4), 320-334.

Ferrari, A. M., and Jones, B. (2012, September). Value and cost effectiveness of conducting a root cause analysis. In *International Pipeline Conference* (Vol. 45158, pp. 559-567). American Society of Mechanical Engineers.

Foroudi, M. M., and Foroudi, P. (2023). Mixed-methods approach. *Researching and Analysing Business: Research Methods in Practice*.

Franklin, U. (2007). Beautiful, functional and frugal. *Alternatives Journal*, *33*(2/3), 56.

Friedline, T., Oh, S., Klemm, T., and Kugiya, J. (2020). Exclusion and marginalization in financial services: Frontline employees as street-level bureaucrats.

G.A. Churchill Jr, " A paradigm for developing better measures of marketing constructs," Journal of marketing research, 16(1), pp.64-73, 1979.

G.V.A., Vasantha, R. Roy, A. Lelah, and D. Brissaud. "A review of product–service systems design methodologies," Journal of Engineering Design, 23, no. 9: 635-659, 2012

Galvin, M. D., and Iannotti, L. 2015. Social enterprise and development: The KickStart model. *VOLUNTAS: International Journal of Voluntary and Nonprofit Organizations*, *26*, 421-441.

Gangidi, P. (2019). A systematic approach to root cause analysis using 3× 5 why's technique. *International Journal of Lean Six Sigma*, *10*(1), 295-310.

George, G., McGahan, A. M., and Prabhu, J. (2012). Innovation for inclusive growth: Towards a theoretical framework and a research agenda. *Journal of management studies*, *49*(4), 661-683.

Gerring, J. (1999). What makes a concept good? A criterial framework for understanding concept formation in the social sciences. *Polity*, *31*(3), 357-393.

Gill, S., Johnson, P., Dale, J., Loudon, G., Hewett, B., and Barham, G. (2005). The traditional design process versus a new design methodology: A comparative case research of a rapidly designed information appliance. In *Home-Oriented Informatics and Telematics* (pp. 209-223). Springer US.

Girija, S., Banerji, B., Batra, N., Paruchuru, M., & Yeediballi, T. (2024). Making frugal innovations inclusive: A gendered approach. *Journal of Cleaner Production*, *434*, 140182.

Glaubitz, J. P. A. (2012). Modern consumerism and the waste problem. *arXiv preprint arXiv:1206.0604*.

Glen, R., Suciu, C., and Baughn, C. (2014). The need for design thinking in business schools. *Academy of management learning and education*, *13*(4), 653-667, doi: 10.5465/amle.2012.0308.

Goldsmith, R. E., Flynn, L. R., and Clark, R. A. (2014). The etiology of the frugal consumer. *Journal of Retailing and Consumer Services*, *21*(2), 175-184.

Gomera, W. C., Suhonen, J., Tukiainen, M., Oreku, G. S., Tedre, M., & Oyelere, S. S. (2021). Usability evaluation of frugal innovation: A case of mobile training for micro businesses in Tanzania. *African Journal of Science, Technology, Innovation and Development*, *13*(2), 133-146.

Goodwin, N., Nelson, J. A., Ackerman, F., and Weisskopf, T. (2008). Consumption and the consumer society. *Global Development and Environment Institute*, *126*.

Govindarajan, V.J. and Trimble, C. (2012). *Reverse innovation: Create far from home, win everywhere*. Harvard Business Press.

Graham, L. J., & Slee, R. (2006). Inclusion?. In *Disability Studies in Education Special Interest Group, American Educational Research Association (AERA) 2006 Annual Conference*.

Granados, N. F., Kauffman, R. J., and King, B. (2008, January). The emerging role of vertical search engines in travel distribution: A newly-vulnerable electronic markets perspective. In *Proceedings of the 41st Annual Hawaii International Conference on System Sciences (HICSS 2008)* (pp. 389-389). IEEE.

Guo, C., and Wu, D. (2019). Canonical correlation analysis (CCA) based multi-view learning: An overview. *arXiv preprint arXiv:1907.01693*.

Gupta, R., Pandit, A., Nirjar, A., & Gupta, P. (2013). husk power systems: bringing light to rural India and tapping fortune at the bottom of the pyramid. Asian Journal of Management Cases, 10(2), 129-143.

Gupta, V. (2011). Corporate response to global financial crisis: a knowledge-based model. *Global Economy Journal*, *11*(2).

H.F. Kaiser, and J. Rice. "Little jiffy, mark IV," Educational and psychological measurement 34(1),pp. 111-117, 1974.

Hamner, S. R., Narayan, V. G., & Donaldson, K. M. (2013). Designing for scale: Development of the remotion knee for global emerging markets. *Annals of biomedical engineering*, *41*(9), 1851-1859.

Hardoon, D. R., Szedmak, S., and Shawe-Taylor, J. (2004). Canonical correlation analysis: An overview with application to learning methods. *Neural computation*, *16*(12), 2639-2664.

Hedlund, C., Stenmark, P., Noaksson, E., and Lilja, J. (2020). More value from fewer resources: how to expand value stream mapping with ideas from circular economy. *International Journal of Quality and Service Sciences*, *12*(4), 447-459.

Heeks, R. (2012). IT innovation for the bottom of the pyramid. *Communications of the ACM*, *55*(12), 24-27.https://doi.org/10.1145/2380656.2380665.

Hempel, C. G. (1970). On the" standard conception" of scientific theories.

Hindocha, C. N., Antonacci, G., Barlow, J., and Harris, M. (2021). Defining frugal innovation: a critical review. *BMJ Innovations*, *7*(4).

Hoffmann, D. (1993). *Frank Lloyd Wright's Fallingwater: the house and its history*. Courier Corporation.

Horn, C., and Brem, A. (2013). Strategic directions on innovation management – A conceptual framework. *Management Research Review*, 36 (10), 939-954

Hossain, M. (2016). Frugal innovation: a systematic literature review. *Available at SSRN 2768254*.

Hossain, M. (2018). Frugal innovation: A review and research agenda. *Journal of cleaner production*, *182*, 926-936.

Hossain, M. (2020). Frugal innovation: Conception, development, diffusion, and outcome. *Journal of Cleaner Production*, *262*, 121456.

Hossain, M. (2021). Frugal innovation and sustainable business models. *Technology in society*, *64*, 101508.
Hossain, M., Agarwal, N., Bhatti, Y., and Levänen, J. (2022). Frugal innovation: Antecedents, mediators, and consequences. *Creativity and Innovation Management*, *31*(3), 521-540.'
Hussein, A. (2009). The use of triangulation in social sciences research: Can qualitative and quantitative methods be combined?. *Journal of comparative social work*, *4*(1), 106-117.
I.T Joliffe and , B.J.T. Morgan, "Principal component analysis and exploratory factor analysis,"Statistical methods in medical research, 1(1), pp.69-95, 1992
Iizuka, T. (2007). An empirical analysis of planned obsolescence. *Journal of Economics & Management Strategy*, *16*(1), 191-226.
Imrie, R., and Hall, P. (2003). *Inclusive design: designing and developing accessible environments*. Taylor & Francis.
Inglis, A. (2008). Approaches to the validation of quality frameworks for e-learning. *Quality Assurance in Education*, *16*(4), 347-362.
Irani, D. (2010, May 19). GE's handheld ECG machine Mac400 hit. *The Economic Times*. https://economictimes.indiatimes.com/ges-handheld-ecg-machine-mac400-hit/articleshow/5947284.cms
J. Levänen and S. Lindemann, "Frugal innovations in circular economy: exploring possibilities and challenges in emerging markets," In The international society for ecological economics 2016 conference, transforming the economy: sustaining food, water, energy and justice. Washington DC, USA.2016
Jehlen, A., 2002. Inclusion by Design. *NEA Today*, *20*(4), pp.8-9.
Jena, A. B., & Philipson, T. J. (2008). Cost-effectiveness analysis and innovation. *Journal of health economics*, *27*(5), 1224-1236.
Jha, S. K., & Krishnan, R. T. (2013). Local innovation: The key to globalisation. *IIMB Management Review*, *25*(4), 249-256.
Johansson-Sk€oldberg, U., Woodilla, J. and Çetinkaya, M. (2013), "Design thinking: past, present and possible futures", Creativity and Innovation Management, Vol. 22 No. 2, pp. 121–146, doi: 10. 1111/caim.12023.
Jonsson, J. O., and Mills, C. (2002). *Cradle to grave*. sociologypress.
Joshi, A., Kale, S., Chandel, S., and Pal, D. K. (2015). Likert scale: Explored and explained. *British journal of applied science and technology*, *7*(4), 396.
Karasz, A., and Singelis, T. M. (2009). Qualitative and mixed methods research in cross-cultural psychology. *Journal of cross-cultural psychology*, *40*(6), 909-916.
Kazmierczak, E. T. (2003). Design as meaning making: from making things to the design of thinking. *Design issues*, *19*(2), 45-59.
Kellaher, L. (2001). Shaping everyday life: beyond design. In *Inclusive housing in an ageing society* (pp. 215-234). Policy Press.
Khalid, H. M. (2006). Embracing diversity in user needs for affective design. *Applied ergonomics*, *37*(4), 409-418.
Khan, A., and Turowski, K. (2016). A survey of current challenges in manufacturing industry and preparation for industry 4.0. In *Proceedings of the First International Scientific Conference "Intelligent Information Technologies for Industry" (IITI'16) Volume 1* (pp. 15-26). Springer International Publishing.

Khubisa, F. M. (2017). *Developing a frugal information system to support very small enterprise business transactions* (Doctoral dissertation).

Kitchenham, B., Brereton, O. P., Budgen, D., Turner, M., Bailey, J., and Linkman, S. (2009). Systematic literature reviews in software engineering–a systematic literature review. *Information and software technology*, *51*(1), 7-15.

Koch, A., Berberich, J., Köhler, J., and Allgöwer, F. (2021). Determining optimal input–output properties: A data-driven approach. *Automatica*, *134*, 109906.

Koerich, G. V., and Cancellier, E. L. P. D. L. (2020). Frugal Innovation: origins, evolution and future perspectives. *Cadernos EBAPE. BR*, *17*, 1079-1093.

Kolko, J. (2015). Design thinking comes of age.Harvard Business Review, Vol. 93 No. 9, pp. 66-71.

Kosko, B., & Isaka, S. (1993). Fuzzy logic. *Scientific American*, *269*(1), 76-81.

Krikke, J. (2005). Near Real-time tsunami computer simulations within reach. *IEEE Computer Graphics and Applications*, *25*(5), 16-21.

Krippendorff, K. (1980). Validity in content analysis. In *Computerstrategien für die Kommunikationsanalyse* (Vol. 69).

Krippendorff, K. (2004). Reliability in content analysis: Some common misconceptions and recommendations.

Kumari, A., Singh, R., & Das, L. K. (2024). A Conceptual Model to Assess the Effectiveness of Frugal Product Design Frameworks. *IEEE Transactions on Engineering Management*.

Kumari, A., Singh, R., and Das, L. K. (2023, December). Frugal Design: An Empirical Conceptualization and Measurement. In *2023 International Conference on Sustainable Technology and Engineering (i-COSTE)* (pp. 1-6). IEEE.

Kuo, A. (2014). Creating social value through frugal innovation. *Tsai SDH, Liu TYC, Jersan Hu J, et al.: Entrepreneurship in Asia: social enterprise, network and grassroots case studies. Singapore: World Scientific Publishing Co. Pte. Ltd*, 53-70.

L. Giannarou and E. Zervas 2014, " Using Delphi technique to build consensus in practice," International Journal of Business Science and Applied Management (IJBSAM), 9(2), pp.65-82, 2014

Labrecque, L. I., Vor Dem Esche, J., Mathwick, C., Novak, T. P., & Hofacker, C. F. (2013). Consumer power: Evolution in the digital age. *Journal of interactive marketing*, *27*(4), 257-269.

Lacy, P., Arnott, J., and Lowitt, E. (2009). The challenge of integrating sustainability into talent and organization strategies: investing in the knowledge, skills and attitudes to achieve high performance. *Corporate Governance: The international journal of business in society*, *9*(4), 484-494.

Lastovicka, J. L., Bettencourt, L. A., Hughner, R. S., & Kuntze, R. J. (1999). Lifestyle of the tight and frugal: Theory and measurement. *Journal of consumer research*, *26*(1), 85-98.

Le Bas, C. (2016). Frugal innovation, sustainable innovation, reverse innovation: why do they look alike? Why are they different?. *Journal of Innovation Economics & Management*, *21*(3), 9-26.

Leech, N. L., Dellinger, A. B., Brannagan, K. B., and Tanaka, H. (2010). Evaluating mixed research studies: A mixed methods approach. *Journal of mixed methods research*, *4*(1), 17-31.

Leliveld, A., and Knorringa, P. (2018). Frugal innovation and development research. *The European Journal of Development Research*, *30*, 1-16.

Lemmens, Y., Guenov, M., Rutka, A., Coleman, P., & Schmidt-Schäffer, T. (2007). Methods to analyse the impact of changes in complex engineering systems. In *7th AIAA ATIO Conf, 2nd CEIAT Int'l Conf on Innov and Integr in Aero Sciences, 17th LTA Systems Tech Conf; followed by 2nd TEOS Forum* (p. 7822).

Leonor, S., Mateus, A. and Martins, S. (2017). Design Metasystem research project: from linear to non-linear processes applied in the improvement of creation and development of start-ups. e-Revista LOGO. 6. 1-25. 10.26771/e-Revista.LOGO/2017.3.01.

Leontief, W. (1987). Input-output analysis. *The new palgrave. A dictionary of economics*, *2*(1), 860-864.

Levänen, J., Hossain, M., Lyytinen, T., Hyvärinen, A., Numminen, S., and Halme, M. (2015). Implications of frugal innovations on sustainable development: Evaluating water and energy innovations. *Sustainability*, *8*(1), 4.D.

Lewis, D. (1970). How to define theoretical terms. *The Journal of Philosophy*, *67*(13), 427-446.

Lewis, D. (1971). Immodest inductive methods. *Philosophy of Science*, *38*(1), 54-63.

Liang, H., Dingel, J., and Diskin, Z. (2006, May). A comparative survey of scenario-based to state-based model synthesis approaches. In *Proceedings of the 2006 international workshop on Scenarios and state machines: model, algorithms, and tools* (pp. 5-12).

Liedtka, J. (2011). Learning to use design thinking tools for successful innovation. *Strategy and Leadership*, *39*(5), 13-19.

Liedtka, J., (2015). Perspective: Linking design thinking with innovation outcomes through cognitive bias reduction. *Journal of product innovation management*, *32*(6), 925-938, doi: 10.1111/jpim.12163.

Liedtke, C., Bienge, K., Wiesen, K., Teubler, J., Greiff, K., Lettenmeier, M., and Rohn, H. (2014). Resource use in the production and consumption system—The MIPS approach. *Resources*, *3*(3), 544-574.

Liefner, I., Losacker, S., and Rao, B. C. (2020). Scale up advanced frugal design principles. *Nature Sustainability*, *3*(10), 772-772.

Lim, C., & Fujimoto, T. (2019). Frugal innovation and design changes expanding the cost-performance frontier: A Schumpeterian approach. *Research Policy*, *48*(4), 1016-1029.

M. Dabić ,T. Obradović ,B. Vlačić, S. Sahasranamam and J. Paul, " Frugal innovations: A multidisciplinary review and agenda for future research," Journal of Business Research, 142, pp.914-929, 2022

Ma, Y., Rong, Y., Ma, Y., and Rong, Y. (2022). Industrial Design Part 1: Elements in Product Development—What Makes a Good Industrial Design?. *Senior Design Projects in Mechanical Engineering: A Guide Book for Teaching and Learning*, 271-297.

Magdoff, F. (2013). The Depletion of the World's Natural Resources. *Monthly Review*.

Mahto, D., and Kumar, A. (2008). Application of root cause analysis in improvement of product quality and productivity. *Journal of Industrial Engineering and management*, *1*(2), 16-53.

Mansoori, Y., and Lackeus, M., (2020). Comparing effectuation to discovery-driven planning, prescriptive entrepreneurship, business planning, lean startup, and design thinking. *Small Business Economics*, *54*, 791-818

Mao, J. (2021, August). An Interpretation of Semiotics in the Display Design of Apple User Experience Store. In *7th International Conference on Arts, Design and Contemporary Education (ICADCE 2021)* (pp. 407-414). Atlantis Press.

Mao, J. Y., Vredenburg, K., Smith, P. W., & Carey, T. (2005). The state of user-centered design practice. *Communications of the ACM*, *48*(3), 105-109.

Marcus, A., Abromowitz, S., and Abulkhair, M. F. (2013). *Design, user experience, and usability*. Berlin/Heidelberg, Germany: Springer.

Maretto, L., Faccio, M., and Battini, D. (2022). A multi-criteria decision-making model based on fuzzy logic and AHP for the selection of digital technologies. *IFAC-PapersOnLine*, *55*(2), 319-324.

Martin, R. (2010), "Design thinking: achieving insights via the 'knowledge funnel'", Strategy and Leadership, Vol. 38 No. 2, pp. 37-41, doi: 10.1108/10878571011029046.

Martin, R. L. (2009). *The design of business: Why design thinking is the next competitive advantage*. Harvard Business Press.

Mashelkar, R. A., & Sridhar, R. (2008). Gandhian Engineering is not just for the poor. *IDEAS-RS*.

Mason, M. (2011). The impact of World War II on women's fashion in the United States and Britain.

Mayring, P. (2004).) Qualitative content analysis. *A companion to qualitative research*, *1*(2), 159-176.

McCloy, R., Beaman, C. P., Frosch, C. A., and Goddard, K. (2010). Fast and frugal framing effects?. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *36*(4), 1043.

McDonald, R., van Bever, D., and Ojomo, E. (2021). Chotukool:"Little Cool," Big Opportunity. *Harvard Business School Case*, 616-620.

McHarg, I. L. (1969). *Design with nature* (pp. 7-17). New York: American Museum of Natural History

McMurray, A. J., Weerakoon, C., and Etse, D. (2019). Exploring the dark side of frugal innovation. In *Frugal Innovation* (pp. 311-336). Routledge.

Meline, T. (2006). Selecting studies for systemic review: Inclusion and exclusion criteria. *Contemporary issues in communication science and disorders*, *33*(Spring), 21-27.

Mendis, K., Thayaparan, M., Kaluarachchi, Y., & Pathirage, C. (2023). Challenges faced by marginalized communities in a post-disaster context: a systematic review of the literature. *Sustainability*, *15*(14), 10754.

Mendonca, V., Moses, A. C., & Sharma, S. (2024). *ReMaterials: Scaling up frugal innovation solutions*. Indian Institute of Management, Ahmedabad.

Miles, R. E., Snow, C. C., Fjeldstad, Ø. D., Miles, G., and Lettl, C. (2010). Designing organizations to meet 21st-century opportunities and challenges. *Organizational Dynamics*, *39*(2), 93-103.

Miller Jr, R. G. (1997). *Beyond ANOVA: basics of applied statistics*. CRC press.

Miller, G. A. (1951). Language and communication.

Mitra, S., and Ghosh, A. K. (2012). A research on effect of attrition over financial performance of the companies in life insurance sector in India. In *National Conference on Emerging Challenges for Sustainable Business* (pp. 731-749).

Modular Pre-fabricated Housing(Energy) https://www.modular.org/2023/12/26/how-modular-construction-leads-to-zero-waste-and-eco-fficiency/

Modular Pre-fabricated Housing(fucntionality): https://www.mdpi.com/2075-5309/14/9/3014

Modular Pre-fabricated Housing(inclusion): https://www.whatdesigncando.com/breakout-sessions/design-innovation-do-more-with-less/

Modular Pre-fabricated Housing(information) https://pinnacleinfotech.com/ways-bim-can-benefit-sustainability-in-building-design-and-construction/#:~:text=This%20entire%20BIM%2Dled%20process,occur%20in%20traditional%20construction%20practices.

Modular Pre-fabricated Housing(material)https://les.mitsubishielectric.co.uk/the-hub/building-materials-go-local

Modular Pre-fabricated Housing(Space) https://www.samanportable.com/modular-house-india-advantages/

Modular Pre-fabricated Housing(SUstainability): https://www.novatr.com/blog/modular-prefabricated-homes

Modular Pre-fabricated Housing(Time) https://www.modular.org/construction-timelines/

Mohamad, M. M., Sulaiman, N. L., Sern, L. C., and Salleh, K. M. (2015). Measuring the validity and reliability of research instruments. *Procedia-Social and Behavioral Sciences*, *204*, 164-171.

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Bmj*, *339*.

Montalbano, G., and Santi, G. (2023). Creative Frugality as a Sustainable Circular Pattern in Architecture and Building Construction. *Engineering Proceedings*, *53*(1), 9.

Mukerjee, K. (2012). Frugal innovation: the key to penetrating emerging markets. *Ivey Business Journal*, *76*(4).

Mulder, I., and Loorbach, D. (2016). Rethinking Design: A critical perspective to embrace societal challenges. In *Can design catalyse the great transition: papers from the transition design symposium* (pp. 16-24).

Narasimhalu, A. D., and Dula, C. (2012) Jayaashree Industries: Revolutionising sanitary pad use in India.

Nasab, H. H., and Milani, A. S. (2012). An improvement of quantitative strategic planning matrix using multiple criteria decision making and fuzzy numbers. *Applied Soft Computing*, *12*(8), 2246-2253.

Neely, A., Richards, H., Mills, J., Platts, K., and Bourne, M. (1997). Designing performance measures: a structured approach. *International journal of operations and Production management*, *17*(11), 1131-1152.
Nelson, H. G., and Stolterman, E. (2014). *The design way: Intentional change in an unpredictable world*. MIT press.
Niroumand, M., Shahin, A., Naghsh, A., & Peikari, H. R. (2020). Frugal innovation enablers: a comprehensive framework. *International Journal of Innovation Science*, *12*(1), 1-20.
Norman, D. A., and Verganti, R. (2014). Incremental and radical innovation: Design research vs. technology and meaning change. *Design issues*, *30*(1), 78-96.
Oliveira, B. G., Liboni, L. B., Cezarino, L. O., Stefanelli, N. O., and Miura, I. K. (2020). Industry 4.0 in systems thinking: From a narrow to a broad spectrum. *Systems Research and Behavioral Science*, *37*(4), 593-606.
Omer, A. M. (2009). Energy use and environmental impacts: A general review. *Journal of renewable and Sustainable Energy*, *1*(5).
Omwansa, T. (2009). M-PESA: Progress and prospects. *Innovations*, *107*, 476.
Oosterwal, D. P. (2010). *The lean machine: how Harley-Davidson drove top-line growth and profitability with revolutionary lean product development*. Amacom.
Ophoff, J., Jensen, A., Sanderson-Smith, J., Porter, M., and Johnston, K. (2014). A descriptive literature review and classification of insider threat research. In *Proceedings of Informing Science and IT Education Conference (InSITE)* (Vol. 2014).
P. Soni and T. Krishnan, R., "Frugal innovation: aligning theory, practice, and public policy," Journal of Indian Business Research, 6(1), pp.29-47, 2014.
P. Upadhyay, and R. M. Punekar, "A framework for designing frugal innovations in marginalised contexts." Journal of Cleaner Production, 410, p. 137170, 2023
Palepu, K., Anand, B. N., and Tahilyani, R. (2011). Tata Nano-The people's car. *Harvard Business School Strategy Unit Case*, (710-420).
Paninchukunnath, A. (2013). Jugaad-the Indian model of frugal innovation. In *Proceedings of the 2013 Annual Conference of the Emerging Markets Conference Board, Published by Nelson Mandela Metropolitan University Business School* (pp. 151-163)
Papalambros, P. Y. (2024). From design optimization to design science: An evolution in design thinking. In *Design Research: The Sociotechnical Aspects of Quality, Creativity, and Innovation* (pp. 23-41). Cham: Springer International Publishing.
Parsons, G. (2015). *The philosophy of design*. John Wiley & Sons.
Patel, N., Mindhe, O., Lonkar, M., Naikare, D., Pawar, S., Bhojwani, V. K., and
Pawar, S. (2021, June). Performance investigation of mitticool refrigerator. In *Techno-Societal 2020: Proceedings of the 3rd International Conference on Advanced Technologies for Societal Applications—Volume 2* (pp. 1051-1061). Cham: Springer International Publishing.
Paul, B., Manuel, M. P., and Alex, Z. C. (2012, March). Design and development of non invasive glucose measurement system. In *2012 1st international symposium on physics and technology of sensors (ISPTS-1)* (pp. 43-46). IEEE.

Pearson, E. S. (1936). Relations between two sets of variates. *Biometrika*, *28*(3-4), 321-377.

Pedroso, I. D., Soares, M. A. F., de Aguiar Dutra, A. R., Cubas, A. L. V., de Andrade, J. B. S. O., & Brem, A. (2023). Frugal innovation development for sustainability: The case of extractivism of the "Butia catarinensis" in Brazil. *Journal of Cleaner Production*, *412*, 137318.

Phalkey, J., & Chattapadhyay, S. (2015). The Aakash tablet and technological imaginaries of mass education in contemporary India. *History and Technology*, *31*(4), 452-481.

Pisoni, A., Michelini, L., and Martignoni, G. (2018). Frugal approach to innovation: State of the art and future perspectives. *Journal of Cleaner Production*, *171*, 107-126.

Pitta, D. A., Guesalaga, R., and Marshall, P. (2008). The quest for the fortune at the bottom of the pyramid: potential and challenges. *Journal of Consumer Marketing*, *25*(7), 393-401.

Pode, R. (2010). Solution to enhance the acceptability of solar-powered LED lighting technology. *Renewable and sustainable energy Reviews*, *14*(3), 1096-1103.

Połeć, W., and Murawska, D. (2021). The Social Constraints on the Preservation and Sustainable Development of Traditional Crafts in a Developed Society. *Sustainability*, *14*(1), 120.

Pollastri, A. R., Epstein, L. D., Heath, G. H., and Ablon, J. S. (2013). The collaborative problem solving approach: Outcomes across settings. *Harvard Review of Psychiatry*, *21*(4), 188-199.

Poon, S. (2017). Designing For Digital Innovation: How Design Is Embracing Change And Technology.

Powell, S. I. (2022). Overconsumption Consumer Behaviour Paradoxes: A Systematic Literature Review.

Prabhu, G. N., and Gupta, S. (2014, July). Heuristics of frugal service innovations. In *Proceedings of PICMET'14 Conference: Portland International Center for Management of Engineering and Technology; Infrastructure and Service Integration* (pp. 3309-3312). IEEE.

Prabhu, J. (2017). Frugal innovation: doing more with less for more. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *375*(2095), 20160372.

Prahalad, C. K. (2005). *The Fortune at the Bottom of the Pyramid*. Financial Times/Prentice Hall.

Prahalad, C. K., and Prahalad, C. K. (2005). *The Fortune at the Bottom of the Pyramid*. Wharton School Pub.

R. Farooq, "An updated paradigm for developing better measures: a review of scale development practices, "Anvesha, 10(2), 42-53, 2017

R. Tiwari and C. Herstatt, "Frugal innovation: A global networks' perspective," Die Unternehmung, 66(3), pp.245-274, 2012

Rabbi, F., Ahamad, R., Ali, S., Chandio, A. A., Ahmad, W., Ilyas, A., and Din, I. U. (2019). Determinants of commercialization and its impact on the welfare of smallholder rice farmers by using Heckman's two-stage approach. *Journal of the Saudi Society of Agricultural Sciences*, *18*(2), 224-233.

Radjou, N., and Prabhu, J. (2014). 4 CEOs who are making frugal innovation work. *Harvard business review*, *28*, 1-6.
Radjou, N., and Prabhu, J. (2015). *Frugal Innovation: How to do more with less*. The Economist.
Radjou, N., Prabhu, J., & Ahuja, S. (2012). *Jugaad innovation: Think frugal, be flexible, generate breakthrough growth*. John Wiley & Sons.
Radjou, N., Prabhu, J., Ahuja, S., and Roberts, N. (2015). Frugal innovation. *How to do more with less. New York: Public Affairs*.
Rajesh, R. (2021). Research Of Customer Experience And Uses Of Uber Cab Services In Mumbai. *International Journal of Application or Innovation in Engineering & Management*, *10*(6), 050-061.
Ramdorai, A., & Herstatt, C. (2015). Frugal innovation in healthcare. *India studies in business and economics*, *127*.
Rao, B. C. (2013). How disruptive is frugal?. *Technology in society*, *35*(1), 65-73.
Rao, B. C. (2019). The science underlying frugal innovations should not be frugal. *Royal Society Open Science*, *6*(5), 180421.
Rao, B. C. (2024). Advanced Frugal Innovations. In *Frugal Engineering: Advent, Design and Production of Frugal Products* (pp. 19-96). Singapore: Springer Nature Singapore.
Ratten V. *Frugal innovation*. 1st ed. Oxon, U.K.: Routledge,2019.
Rees, F. (2006). *Johannes Gutenberg: Inventor of the printing press*. Capstone.
Riedmaier, S., Ponn, T., Ludwig, D., Schick, B., & Diermeyer, F. (2020). Survey on scenario-based safety assessment of automated vehicles. *IEEE access*, *8*, 87456-87477.
Roiland, D. (2016). Frugality, A Positive Principle to Promote Sustainable Development. *Journal of Agricultural and Environmental Ethics*, 29 (4), 571-585.
Rösch, N., Tiberius, V., and Kraus, S. (2023). Design thinking for innovation: context factors, process, and outcomes. *European Journal of Innovation Management*, *26*(7), 160-176.
Ross, A., and Willson, V. L. (2018). *Basic and advanced statistical tests: Writing results sections and creating tables and figures*. Springer.
Rossetto, D. E., & Frankwick, G. L. (2018). A new scale proposition for measuring Frugal Innovation: scale development process and validation. *Anais*.
S. Tesic, B. Bajic, I. Cosic and A. Rikalovic , “ Frugal innovation in industry 4.0: The Identification of key indicators,” Annals of DAAAM and Proceedings, 10(2), 2021.
Saaty, T. L. (2016). The analytic hierarchy and analytic network processes for the measurement of intangible criteria and for decision-making. *Multiple criteria decision analysis: state of the art surveys*, 363-419.
Saqib, N., and Mathu, A. A. (2024). Frugal Business Model Innovation in an Indian Emerging Market: A Case Research of Aravind Eye Care System. In *Fostering Global Entrepreneurship Through Business Model Innovation* (pp. 184-205). IGI Global.
Sarker, A., Ghosh, M. K., Islam, T., Bilal, M., Nandi, R., Raihan, M. L., ... and Kim, J. E. (2022). Sustainable food waste recycling for the circular economy in

developing countries, with special reference to Bangladesh. *Sustainability*, *14*(19), 12035.
Saurio, R., Hennala, L., Pekkarinen, S., and Melkas, H. (2022). Design Thinking and Welfare: A Focus on Information Design. In *Different Perspectives in Design Thinking* (pp. 165-201). CRC Press.
Savvina, O. V. (2017). STEVE JOBS'UNDERSTANDING OF DESIGN: ETHICAL DIMENTION. *RUDN Journal of Philosophy*, *21*(3), 371-378.
Schaffner, M. A., Shihong, M. W., Ross, A. M., and Rhodes, D. H. (2013). Enabling design for affordability: an epoch-era analysis approach.
Schleinkofer, U., Herrmann, T., Maier, I., Bauernhansl, T., Roth, D., & Spath, D. (2019). Development and evaluation of a design thinking process adapted to frugal production systems for emerging markets. *Procedia Manufacturing*, *39*, 609-617.
Schreier, M. (2012). Qualitative content analysis in practice. *Qualitative content analysis in practice*, 1-280.
Schuster, T. (2014). Govindarajan, V., Trimble, C., Reverse Innovation: Create Far from Home, Win Everywhere, Harvard Business Review Press, 2012.
Scoones, I. (2007). Sustainability. *Development in practice*, *17*(4-5), 589-596.
Sehgal, V., Dehoff, K., & Panneer, G. (2010). THE INNOVATORS-The Importance of Frugal Engineering-Providing new goods and services to" bottom of the pyramid" customers requires a radical rethinking of product development. *Strategy and Business*, *59*(1), 20-37.
Seidel, V. P., and Fixson, S. K., (2013). Adopting design thinking in novice multidisciplinary teams: The application and limits of design methods and reflexive practices. *Journal of Product Innovation Management*, *30*, 19-33, doi: 10.1111/jpim.12061.
Shahid, M. S., Hossain, M., Shahid, S., and Anwar, T. (2023). Frugal innovation as a source of sustainable entrepreneurship to tackle social and environmental challenges. *Journal of Cleaner Production*, *406*, 137050.
Shahin, A., Barati, A., and Geramian, A. (2017). Determining the critical factors of radical innovation using an integrated model of fuzzy analytic hierarchy process-fuzzy Kano with a case research in Mobarakeh steel company. *Engineering Management Journal*, *29*(2), 74-86.
Shapira, H., Ketchie, A., and Nehe, M., (2017). The integration of design thinking and strategic sustainable development. *Journal of Cleaner Production*, *140*, 277-287, doi: 10.1016/j.jclepro.2015.10.092.
Sharma, A., and Iyer, G. R. (2012). Resource-constrained product development: Implications for green marketing and green supply chains. *Industrial Marketing Management*, *41*(4), 599-608.
Sharma, M. G., and Kumar, S. (2025). Probing frugal innovation from the quality lens. *The TQM Journal*, *37*(2), 592-610.
Sharma, M. G., and Kumar, S. (2025). Probing frugal innovation from the quality lens. *The TQM Journal*, *37*(2), 592-610.
Sharma, N. G. (2013). Narayana Health–Heart in the Right Place!. *Cases in management*, 85-106.
Shavitt, S., Jiang, D., and Cho, H. (2016). Stratification and segmentation: Social class in consumer behavior. *Journal of Consumer Psychology*, *26*(4), 583-593.

Shrouti, C., Franciosa, P., Ceglarek, D., 2013, Root Cause Analysis of Product Service Failure Using Computer Experimentation Technique, In Proceedings of the 2nd Through-lifecycle Engineering Services Conference, Procedia CIRP, 11: 44-49.

Simanis, E. (2012). Reality check at the bottom of the pyramid. *Harvard Business Review*, *90*(6), 120-125.

Simo, M. (2013). Challenges of Companies Operating in BoP Markets. Case of Albania. *Academic Journal of Interdisciplinary Studies*, *2*.

Simula, H., Hossain, M., and Halme, M. (2015). Frugal and reverse innovations–Quo Vadis?. *Current science*, 1567-1572.

Singh, R., and Mangat, N. S. (2013). *Elements of survey sampling* (Vol. 15). Springer Science & Business Media.

Singh, R., Mangat, N. S., Singh, R., and Mangat, N. S. (1996). Stratified sampling. *Elements of survey sampling*, 102-144.

Singh, R., Seniaray, S., and Saxena, P. (2020). A framework for the improvement of frugal design practices. *Designs*, *4*(3), 37.

Søndergaard, M. L. J., and Hansen, L. K. (2017). Designing with Bias and Privilege?. *Nordes*, *7*(1).

Soni, P., and T. Krishnan, R. (2014). Frugal innovation: aligning theory, practice, and public policy. *Journal of Indian Business Research*, 6 (1), 29-47.

Sonnentag, S., and Frese, M. (2002). Performance concepts and performance theory. *Psychological management of individual performance*, *23*(1), 3-25.

Speijker, L. J. P., Kos, J., Blom, H. A. P., and Van Baren, G. B. (2000). Probablistic wake vortex safety assessment to evaluate separation distances for ATM operations

Statistics, L. (2013). Descriptive and inferential statistics. *Retrieved from*.

Steadman, P. (2008). *The evolution of designs: biological analogy in architecture and the applied arts*. Routledge.

Subramanian, R. (2015). SELCO solar light private limited: A social enterprise's scaling up challenge. *Asian Journal of Management Cases*, *12*(2), 172-182.

Suddaby, R. (2010). Construct clarity in theories of management and organization: Editor's comments. *Academy of Management Review*, *35*(3), 346-357. https://doi.org/10.5465/amr.35.3.zok346

Suherman, S., and Vidákovich, T. (2022). Assessment of mathematical creative thinking: A systematic review. *Thinking Skills and Creativity*, *44*, 101019.

Tesfaye, L. A., and Fougère, M. (2022). Frugal innovation hijacked: The co-optive power of co-creation. *Journal of Business Ethics*, *180*(2), 439-454.

The Economist (2010). In praise of techno-austerity, 395(8686), 14. Retrieved October 29, 2014, from http://www.economist.com/node/16321516.

The Economist. (2010a, April 15th). First break all the rules: The charms of frugal innovation. *The Economist*. http://www.economist.com/node/15879359

The New Plastics Economy: Rethinking the future of plastics & catalysing action. (n.d.). https://www.ellenmacarthurfoundation.org/the-new-plastics-economy-rethinking-the-future-of-plastics-and-catalysing?sortBy=rel

Tipton, E., Hedges, L., Vaden-Kiernan, M., Borman, G., Sullivan, K., and Caverly, S. (2014). Sample selection in randomized experiments: A new method using propensity score stratified sampling. *Journal of Research on Educational Effectiveness*, *7*(1), 114-135.

Tiwari, R., and Herstatt, C. (2012). Frugal innovation: A global Networks' perspective. *Die Unternehmung*, 66 (3), 245-274.

Tiwari, R., and Herstatt, C. (2012). Open global innovation networks as enablers of frugal innovation: propositions based on evidence from India. *Hamburg University of Technology, Technology and Innovation Management, Working Paper*, (72).

Tiwari, R., and Herstatt, C. (2013). 'Too Good'to Succeed? Why Not Just Try'Good Enough'! Some Deliberations on the Prospects of Frugal Innovations. *Why Not Just Try'Good Enough*.

Tiwari, R., Fischer, L., and Kalogerakis, K. (2016). Frugal innovation in scholarly and social discourse: An assessment of trends and potential societal implications. *Working paper//Technologie-und Innovationsmanagement, Technische Universität Hamburg-Harburg= Arbeitspapier*.

Tiwari, R., Kalogerakis, K., and Herstatt, C. (2014). Frugal innovation and analogies: some propositions for product development in emerging economies.

Trimble, C., and Govindarajan, V. (2012). Reverse innovation: create far from home, WIN everywhere. *Boston, Massachusetts: Harvard Business School Press Books*.

Trompette, P., and Cholez, C. (2023). Frugal energy and the global markets of pico solar systems. In *Handbook on Frugal Innovation* (pp. 313-329). Edward Elgar Publishing.

Tukker, A., and Tischner, U. (2006). Product-services as a research field: past, present and future. Reflections from a decade of research. *Journal of cleaner production*, *14*(17), 1552-1556.

UN Environment Programme (UNEP), https://www.unep.org/explore-topics/resource-efficiency/about-resource-efficiency

United Nations Department of Economic and Social Affairs, Population Division. "World Population Prospects 2022: Summary of Results. UN DESA/POP/2022/TR/NO. 3, 2022.

Upadhyay, P., and Punekar, R. M. (2023). A framework for designing frugal innovations in marginalised contexts. *Journal of Cleaner Production*, *410*, 137170.

Utterback, J. M., Ekman, S., Sanderson, S. W., Vedin, B. A., Verganti, R., Tether, B., and Alvarez, E. (2006). *Design-inspired innovation*. World Scientific.

Vitta, M., and Nelles, J. (1985). The meaning of design. *Design Issues*, 3-8.

Von Zedtwitz, M., Corsi, S., Søberg, P. V., & Frega, R. (2015). A typology of reverse innovation. *Journal of Product Innovation Management*, *32*(1), 12-28.

Vos, D. A. (2018). Nike Flagship Façade–Design, Engineering and Testing. *ce/papers*, *2*(5-6), 205-215.

Walters, A. (2008). *A performance evaluation of the lifestraw: a personal point of use water purifier for the developing world* (Master's thesis, The University of North Carolina at Chapel Hill).

Wang, H. T., Smallwood, J., Mourao-Miranda, J., Xia, C. H., Satterthwaite, T. D., Bassett, D. S., and Bzdok, D. (2020). Finding the needle in a high-dimensional

haystack: Canonical correlation analysis for neuroscientists. *NeuroImage*, *216*, 116745.
Webb, M. M., Bridges, P., Aruparayil, N., Mishra, A., Bains, L., Hall, R. and Culmer, P. (2021). Designing devices for global surgery: evaluation of participatory and frugal design methods. *IJS Global Health*, *4*(1), e50.
Weber, R. P. (1990). Basic content analysis (Vol. 49). Sage.
Weenink, D. (2003, August). Canonical correlation analysis. In *Proceedings of the Institute of Phonetic Sciences of the University of Amsterdam* (Vol. 25, pp. 81-99). Amsterdam: University of Amsterdam.
Werner, T. T., Mudd, G. M., and Jowitt, S. M. (2015). Indium: key issues in assessing mineral resources and long-term supply from recycling. *Applied Earth Science*, *124*(4), 213-226.
Weyrauch, T., & Herstatt, C. (2017). What is frugal innovation? Three defining criteria. *Journal of frugal innovation*, *2*, 1-17.
Weyrauch, T., Herstatt, C., and Tietze, F. (2020). The objective–conflict–resolution approach: A novel approach for developing radical and frugal innovation. *IEEE transactions on engineering management*, *68*(3), 699-712.10.1109/TEM.2020.3000924
Whiteley, N. (1993). *Design for society*. Reaktion books.
Williamson, P. J. (2010). Cost innovation: preparing for a 'value-for-money'revolution. *Long Range Planning*, *43*(2-3), 343-353..https://doi.org/10.1016/j.lrp.2009.07.008
Wind, Y., and Saaty, T. L. (1980). Marketing applications of the analytic hierarchy process. *Management science*, *26*(7), 641-658.
Witkowski, T. H. (2010). A brief history of frugality discourses in the United States. *Consumption, Markets and Culture*, *13*(3), 235-258.
Wohlfart, L., Bünger, M., Lang-Koetz, C., and Wagner, F. (2016). Corporate and grassroot frugal innovation: a comparison of top-down and bottom-up strategies. *Technology Innovation Management Review*, *6*(4), 5-17. 10.22215/timreview/977
Wolff, E. N. (1994). Productivity measurement within an input-output framework. *Regional Science and Urban Economics*, *24*(1), 75-92.
Womack, J. P., Jones, D. T., and Roos, D. (1990). The machine that changed the world: The story of lean production. *New York: Rawson Associates*, *85*.
Wong, K. C., Woo, K. Z., and Woo, K. H. (2016). Ishikawa diagram. *Quality Improvement in Behavioral Health*, 119-132.
Wooldridge, A. (2010). First break all the rules: The charms of frugal innovation. *The Economist*, *1*(4), 3-5.
Woolridge, A. 2010. The world turned upside down. A special report on innovation in emerging markets. *The Economist,* April 15. Retrieved April 20, 2010, from http://www.economist.com/node/15879369.
World Bank Group. (2018, October 17). Nearly Half the World Lives on Less than $5.50 a Day. *World Bank*. https://www.worldbank.org/en/news/press-release/2018/10/17/nearly-half-the-world-lives-on-less-than-550-a-day
World Development Report (2017): Governance and the Law. (n.d.). World Bank. https://www.worldbank.org/en/publication/wdr2017

Woschke, T., Haase, H., and Kratzer, J. (2017). Resource scarcity in SMEs: effects on incremental and radical innovations. *Management Research Review*, *40*(2), 195-217.

X. Xing, J. Wang,T. Liu,H. Liu. And Y. Zhu,"How energy consumption and pollutant emissions affect the disparity of public health in countries with high fossil energy consumption," International Journal of Environmental Research and Public Health, 16(23), p.4678,2019.

Y. Ding, "Impacts of affluence and overexploitation of natural resources," Environment and Development,1-20, 2003.

Yu, Q., Wang, Y., Van Le, Q., Yang, H., Hosseinzadeh-Bandbafha, H., Yang, Y., ... and Peng, W. (2021). An overview on the conversion of forest biomass into bioenergy. *Frontiers in Energy Research*, *9*, 684234.

Yuan, S., and Tao, C. (1999). Development of conflation components. *Proceedings of geoinformatics*, *99*, 1-13. 10.13140/2.1.4454.5924

Zeschky, M. B., Winterhalter, S., & Gassmann, O. (2014). From cost to frugal and reverse innovation: Mapping the field and implications for global competitiveness. *Research-Technology Management*, *57*(4), 20-27.

Zeschky, M., Widenmayer, B., & Gassmann, O. (2011). Frugal innovation in emerging markets. *Research-Technology Management*, *54*(4), 38-45.

Zhang, S., Su, R., Zhao, Y., Liu, J., & Li, C. (2023). Applying enterprises' frugal innovation in ecologically vulnerable areas: A fuzzy-set qualitative comparative analysis of the influence paths. *Sustainability*, *15*(9), 7658.

Zhou, Z., Ataee Tarzanagh, D., Hou, B., Tong, B., Xu, J., Feng, Y., ... and Shen, L. (2024). Fair canonical correlation analysis. *Advances in Neural Information Processing Systems*, *36*.

List of Publications

Published Papers
Journal:

3. Kumari, A., Singh, R., and Das, L. K. "A Conceptual Model to Assess the Effectiveness of Frugal Product Design Frameworks*, IEEE Transactions on Engineering Management*.

4. Kumari, A., Singh, R., and Das, L. K. (2025). Uncovering The Barriers: The Root Causes Of Frugal Design Failure. *International Journal of Environmental Sciences*, *11*(11s), 1061–1076.

Conference:

3. Kumari, A., Singh, R., and Das, L. K. (2023, December). Frugal Design: An Empirical Conceptualization and Measurement. In *2023 International Conference on Sustainable Technology and Engineering (i-COSTE)* (pp. 1–6). IEEE.

4. Kumari, A., Singh, R., and Das, L. K. (2025). "An approach to evaluate the Accessibility and inclusion of public space," *in Artificial Intelligence in Computational Material Science: Methods and Applications*

Communicated/under review Papers:

1. Kumari, A., Singh, R., & Das, L. K. "An Approach to Developing a Frugal Design Thinking Framework," Journal of Mechanical Design.

2. Kumari, A., Singh, R., & Das, L. K. "The Frugal Innovation Pyramid: A Taxonomy of Innovation Phenomena in the Frugal Product Design Field," Journal of Advanced Design.

3. Kumari, A., Singh, R., & Das, L. K. "Redefining Frugal Innovation: Insights from Semantics and Pragmatic Perspective," Technovation.

4. Kumari, A., Singh, R., & Das, L. K. "Fostering Frugal innovation: A stakeholder-centered design thinking framework," Discover Sustainability.

5. Kumari, A., Singh, R., & Das, L. K. "An Input-Output Model for Frugal Design: A Framework for Resource-Conscious Innovation" IEEE Transactions on Engineering Management.

A Conceptual Model to Assess the Effectiveness of Frugal Product Design Frameworks

Publisher: IEEE Cite This PDF

Anuradha Kumari ; Ravindra Singh ; Lalit Kumar Das All Authors

Abstract:
In contrast to the traditional design approach, the frugal design method seeks to create "more value with fewer resources." Frugal product design frameworks evolved as an essential instrument for developing innovative solutions for resource-constrained areas. However, these frameworks have not been extensively examined for their effectiveness in achieving desired outcomes. The study proposes a conceptual assessment model to assess the efficacy of frugal product design frameworks. The model is based on existing literature on frugal design and identifies the key criteria for being frugal (i.e., core functionality, cost reduction, and optimal performance). Furthermore, the user experience of (n = 200 users) was also incorporated into the model to provide valuable and relevant insight. The proposed model is used to analyze the frugality of the framework, and the framework can be improved by incorporating the criteria that the designer has neglected. Identifying frequently neglected frugality criteria can lead to the refinement of future frugal design strategies. The industry's primary goal in the modern marketplace is to provide consumers with functional, affordable, and optimal-performance products. This study offers an assessment method for frugal product design in an effort to achieve this goal. This model enables businesses to ensure the frugality of product design frameworks in the early stages of the product design process.

Published in: IEEE Transactions on Engineering Management (Volume: 71)

Page(s): 11734 - 11745

DOI: 10.1109/TEM.2024.3429159

Date of Publication: 16 July 2024

Publisher: IEEE

ISSN Information:

I. Introduction

In the modern world of change, where resource restrictions, inclusive growth, and technological considerations are crucial, frugal product design has evolved as an effective approach to delivering value for bot[...] ugal design (FD) addresses marginalized markets and

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 11s, 2025
https://www.theaspd.com/ijes.php

Uncovering The Barriers: The Root Causes Of Frugal Design Failure

Anuradha Kumari[1*], Dr. Ravindra Singh[2], Prof. Lalit Kumar Das[3]

[1]Research Scholar, Department of Design, Delhi Technological University, Delhi, India*
Email: raizada53@gmail.com, ORCID ID: 0000-0001-7635-4890
[2]Assistant Professor, Department of Design, Delhi Technological University, Delhi, India
[3]Honorary Distinguished Faculty, Department of Design, Delhi Technological University, Delhi, India

Abstract
Frugal Design approach aims to develop "more value with less resources," especially for resource-scarce environments. Despite its potential, most frugal design initiatives do not achieve their proposed goals because of systemic inefficiencies and undiscovered constraints. This study examines the causes of failure in frugal design through an in-depth analysis of two case studies that were originally designed with frugal motives but, after being examined, did not satisfy established criteria of frugality. A three-step (Ishikawa diagram, prioritization, and Five Whys method) Root Cause Analysis (RCA) methodology with closed-loop product life cycle analysis was utilized. The analysis identified the 65 causes (56 inter-loop and 9 intra-loop), out of which 51 were critical ones, and reduced them to five major root causes, which were mainly associated with the inefficient use of key input resources: materials, energy, information, space, and time. The results highlight the need to embed resource optimization within every stage of the lifecycle to balance frugal design goals. This research adds to the emerging literature on sustainable and inclusive product development by providing a systematic approach to diagnose and resolve frugal design practice's barriers.

Keywords: *Frugal design, Root Cause Analysis, Closed-loop product lifecycle, Sustainability.*

1 Introduction

Frugal Design (FD) has emerged as a valuable approach to address the world's most pressing challenges, i.e., resource constraints [1], economic disparity [2], and sustainability by focusing on affordability and accessibility without diminishing the functionality and quality of the product. FD is transformational for developed and emerging economies [3];[4]. Its value proposition is to develop solutions that empower the underprivileged, facilitate economic inclusion, and drive sustainable consumption patterns [5]. However, the transition from idea to action is long and arduous. As much as there are inspiring stories of success, many organizations fail to develop frugal design as it fails to meet the frugality criteria (i.e., substantial cost reduction, optimum performance level, and core functionality) [6].

These recurring frugal design failures frequently arise due to the lack of understanding of the need for optimal utilization of resources throughout the life cycle of a product that tends to be complex [7]. Whereas current literature broadly discusses the advantages of frugal design frameworks, there is still a quintessential lack of knowledge regarding why frugal design does not work in real-life practice [8]. It is important to address this gap to help designers, policymakers, and companies create inclusive and sustainable solutions for resource-poor contexts. This study aims to identify the root causes for the failure of frugal design through a rigorous examination of the barriers faced throughout the product life cycle (including raw material extraction to the end-of-life phase) [9].

This study identifies the root causes of frugal design failure with the help of Root Cause Analysis (RCA) techniques based on a closed-loop frugal product lifecycle modeling strategy [10]. Designers and manufacturers can successfully address concerns about divergence from frugality criteria by determining the particular causes that caused the variances and adopting targeted techniques.

2 Closed-loop frugal product lifecycle modeling

Frugal Design: An Empirical Conceptualization and Measurement

Anuradha Kumari
Research Scholar
Department of Design, Delhi Technonological University,
Delhi, India
anuradha_2k19phddes02@dtu.ac.in

Dr. Ravindra Singh,
Assistant Professor,
Department of Design, Delhi Technological University,
Delhi, India
ravindra@dtu.ac.in

Prof. Lalit Kumar Das,
Honorary Distinguished Faculty,
Department of Design, Delhi Technological University,
Delhi, India
lalitdas@dtu.ac.in

2023 International Conference on Sustainable Technology and Engineering (i-COSTE) | 979-8-3503-2971-1/23/$31.00 ©2023 IEEE | DOI: 10.1109/I-COSTE60462.2023.10500807

Abstract- **Designers/Engineers must practice Frugal design to address rising cost-conscious consumption. However, It has been observed that the conception of frugal design and its measurement scale have not yet been created. A three-stage mixed-method research approach was used to identify and validate the frugal design measuring attributes. Stage 1 determined initial frugal design attributes using existing literature research, word frequency count analysis, and expert review content analysis. Survey research (n = 250) was undertaken in Stage 2, and a Principal Component Analysis (PCA) was carried out to refine the preliminary attributes. The final stage involved a survey with a sample of (n=500) Brazilians. To validate the final attribute for gauging frugal design, the Delphi consensus method was used). The frugal design scale provides a framework for organizations to assess frugality based on minimizing inequalities amongst diverse income groups and maximizing well-being by delivering efficient solutions for all groups of people.**

Keywords: Frugal Design, Mixed approach, Content validity, Attributes.

I. Introduction

According to the United Nations Organization (UNO), there are approximately 8 billion people on the planet, of which 648 million people in emerging nations are uncovered to acute poverty and struggle for their livelihood. It is anticipated that this population number will rise to 9.7 billion by 2050 [1]. This extremely rapid population growth will undoubtedly lead to many problems related to the overconsumption of resources and a decline in quality of living. As the demand for resources continues to rise, so will energy consumption, resulting in environmental challenges, i.e., biodiversity loss and climate change. Also, the long-term availability of resources required to maintain the expanding population may become a concern [2]. Expansion of global markets will raise the costs of essential resources and inaccessible products, causing social stratification and inequality and an unsafe environment for a living [3].

Various solutions, such as the 12R doctrine, circular economy, shared economy, etc., have been developed to tackle these burning issues, as mentioned above, but none of them appear to be effective in solving them effectively [4]. Frugal design is a comparatively new type of approach that gained significant growth in an era of scarce resources [5]. It is a concept that emerges regardless of financial, technological, human, and other resource constraints. It produces economic outcomes catering to marginalized society's fundamental needs [6]. A few examples of Frugal Design are Selco: solar energy; in India, solar energy is provided to people at the bottom of the social and economic pyramid; Mitti cool; a refrigerator that runs without battery, Voda-phone mobile: solar power mobile, M-Pesa, etc. [7].

Although frugal design has increasingly gained scholarly attention as an approach to developing affordable solutions, there is a gap in the literature regarding a comprehensive understanding of this approach [8]. The literature has mainly concentrated on grassroots movements until now when describing this process [9]. It is worth mentioning that frugal design may include attributes other than just low-cost innovation and material constraints method. A specific requirement is to investigate and validate frugal design conception from a multi-attribute aspect. Earlier investigations, such as[10], have highlighted dimensions of frugal design; however, their research on frugal design was primarily qualitative. Therefore, the question remains: what attributes are required in the early design phase for creating the frugal design? The purpose of this study is to construct and validate a measurement scale to give an appropriate response to this question. Based on the practical importance of frugal design and the discovered gaps in the literature about the attributes of frugal design, the current study tries to fill the gap by empirically conceptualizing frugal design.

The study adds a significant contribution to the existing reservoir of knowledge on frugal design. The study creates a consistent and valid multi-attribute frugal design measurement scale. Additionally, the study explains how a frugal design is conceptualized empirically from customers' perspectives. The present study uses a mixed-method approach with multiple stages and a variety of methodologies to investigate and validate the assessment of frugal design. Finally, defining the

979-8-3503-2971-1/23/$31.00 ©2023 IEEE

An approach to evaluate the Accessibility and inclusion of public space

Anuradha Kumari[1] [0000-0001-7635-4890], Ravindra Singh[2] [0000-0001-6183-6918], Lalit Kumar Das[3]

[1]Research Scholar, Delhi Technological University, Delhi, India
[2]Assistant Professor, Delhi Technological University, Delhi, India
[3]Honorary Distinguished Faculty, Department of Design, Delhi Technological University, Delhi, India

Abstract
Access to public spaces is a crucial problem for people with disabilities as it instantly impacts their capacity to participate fully in society. As a result, including universal design in design practices is critical for providing infrastructure and services that allow individuals to live freely and equitably and participate in society. However, despite growing study in this field, universal design principles remain unreliable; hence, there is a need to establish a reliable approach to evaluating the accessibility of public spaces while addressing the needs and desires of people with diverse abilities. The Importance-performance analysis (IPA) approach was adopted to evaluate the accessibility of a college cafeteria. Affinity mapping techniques were used to determine the four fundamental user needs: functionality, usefulness, sociability, and aesthetics. According to the findings, all four needs should be considered while developing an accessible and inclusive design.

Key Words: Accessibility; Inclusion; Universal Design; Importance-Performance Analysis; Design Practice.

1. INTRODUCTION

According to the "World Health Organization" (WHO), more than 1.3 billion people worldwide have some form of disability (WHO, W., 2011). People with disabilities are a significant minority group that feels excluded or marginalized from their community due to inadequate infrastructure and inappropriate public space planning (Aiden & McCarthy, 2014). Public space is one that everyone has the right to access without being excluded or labeled due to their economic, physical, or social status. To make an inclusive and cohesive society, it is essential to consider all sets of users during the initial design phase. Incomplete knowledge, understanding of the context, and user exclusion are the key factors of inclusiveness and insufficient inaccessibility (Agarwal& Steele, 2016). To make an effective, accessible, and inclusive environment, Universal Design (UD) needs to be integrated into the design process (Preiser and Ostroff, 2011). Integration of UD eliminates the accessibility barriers for people with disabilities and improvises the public spaces' simple and intuitive for everyone, including people with mobility problems (permanent and temporary), visually impaired, pregnant women, children, and people with communication problems (Agarwal & Chakravarti, 2014).

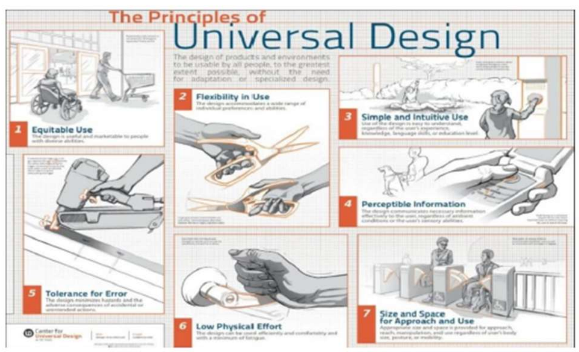


Fig. 1. Universal Design Principles (Burgstahler, 2009).

An architect Ronald L. Mace and a team of researchers pioneered the term Universal design- "A design of a product, services, and environment to make them accessible to all people regardless of their age, disability, etc. " (Mace,1985). The Centre for Universal Design at North Carolina State University developed the seven Universal Design principles as shown in Fig. 1(Burgstahler, 2009).

The main goal of universal design is to impose a high value of inclusiveness, equality, and diversity (Burgstahler, S. 2009). Accessibility in public spaces is one of the most important issues, but it has not been adequately addressed.

https://i-coste.org/i-coste2023/

Certificate of Participation

Persented to Paper ID: **1072**

Anuradha Kumari, Dr. Ravindra Singh, Prof. Lalit Kumar Das

Frugal Design: An Empirical Conceptualization and Measurement

for participating at

9th IEEE International Conference on Sustainable Technology and Engineering 2023 (IEEE i-COSTE 2023)
Shangri-La Fijian Resort, Fiji | Dec 4 - Dec 6, 2023

GM Shafiullah

Associate Professor GM Shafiullah
General Chair
IEEE i-COSTE, Fiji 2023

IEEE · IEEE COMPUTER SOCIETY · HarryButler Institute · NPS Australia

Shobhit Institute of Engineering & Technology Deemed to-be-University
EDUCATION EMPOWERS
34 YEARS OF ACADEMIC EXCELLENCE

INTERNATIONAL CONFERENCE ON INNOVATIVE RESEARCH IN SCIENCE AND TECHNOLOGY

(May 23-25, 2023)

Certificate of Appreciation

This is to certify that Prof./Dr./Ms./Mr. Anuradha Kumari & Ravindra Singh Lalit K. Das of Delhi Technological University has presented a research paper/attended/volunteered in **IRST-2023** organized by **Shobhit Institute of Engineering and Technology [NAAC 'A' Grade Accredited** Deemed to-be University], Meerut.

(University Seal)

Dr. ....
Organiser

RK Jain
Dr. ....
Convenor

SPONSORED BY · SUPPORTED BY · PROCEEDING IN · Springer · separations · INSTITUTION'S INNOVATION COUNCIL

Shobhit Institute of Engineering & Technology [NAAC 'A' Grade Accredited Deemed to-be University established u/s 3 of UGC Act, 1956], NH-58, Modipuram, Meerut - 250110, Delhi NCR

Curriculum Vitae

Anuradha Kumari

Research Scholar/ Guest Faculty

Education

- Ph.D. in Design
  2019 - Present
- M.E. in Industrial Design
  2014 - 2016
- B.E. in Electronics and Communication Engineering
  2010-2014

Experience

- Guest Faculty
  Netaji Subhash University of Technology, Delhi
  2022- 2025.
- Research Scholar/Guest Faculty
  Delhi Technological University, Delhi
  2019 - Present
- Assistant Professor
  Lovely Professional University, Punjab
  2016- 2019

Technical Skill

Graphic Design

3D Design Software

Others Software

Research Publication

- Kumari, A., Singh, R., & Das, L. K. (2024). A Conceptual Model to Assess the Effectiveness of Frugal Product Design Frameworks. IEEE Transactions on Engineering Management.
- Kumari, A., Singh, R., & Das, L. K. (2023, December). Frugal Design: An Empirical Conceptualization and Measurement. In 2023 International Conference on Sustainable Technology and Engineering (i-COSTE) (pp. 1-6). IEEE.
- Kumari, A., & Singari, R. M. (2023). The Study of Human Behavior and Physical Ergonomics in the Workplace. International Journal of Design and Allied Sciences (IJDAS), 2(1), 1–11
- Kumari, A., Singh, R., Das L.K,(2023). An approach to evaluate the Accessibility and inclusion of public space. in the International Conference on Innovative Research in Science and Technology (IRST-2023), Springer Nature.
- Kumari, A., Sharma, V., Prakash, N.R., & Randhawa, J.S. (2016). Methods for Stress Assessment: A Review. International journal of scientific research in science, engineering, and technology, 2, 761-764.
- Kumari, A., & Singh, R. (2019, December). Evaluation of Work-Related Stress Amongst Industrial Workers. In International Conference on Advanced Production and Industrial Engineering (pp. 315-328). Singapore: Springer Nature Singapore.