

Uncovering The Barriers: The Root Causes Of Frugal Design Failure

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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

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 [11], as shown in Fig. 1.

2.1 Inter-loop of Frugal Product Lifecycle Modeling

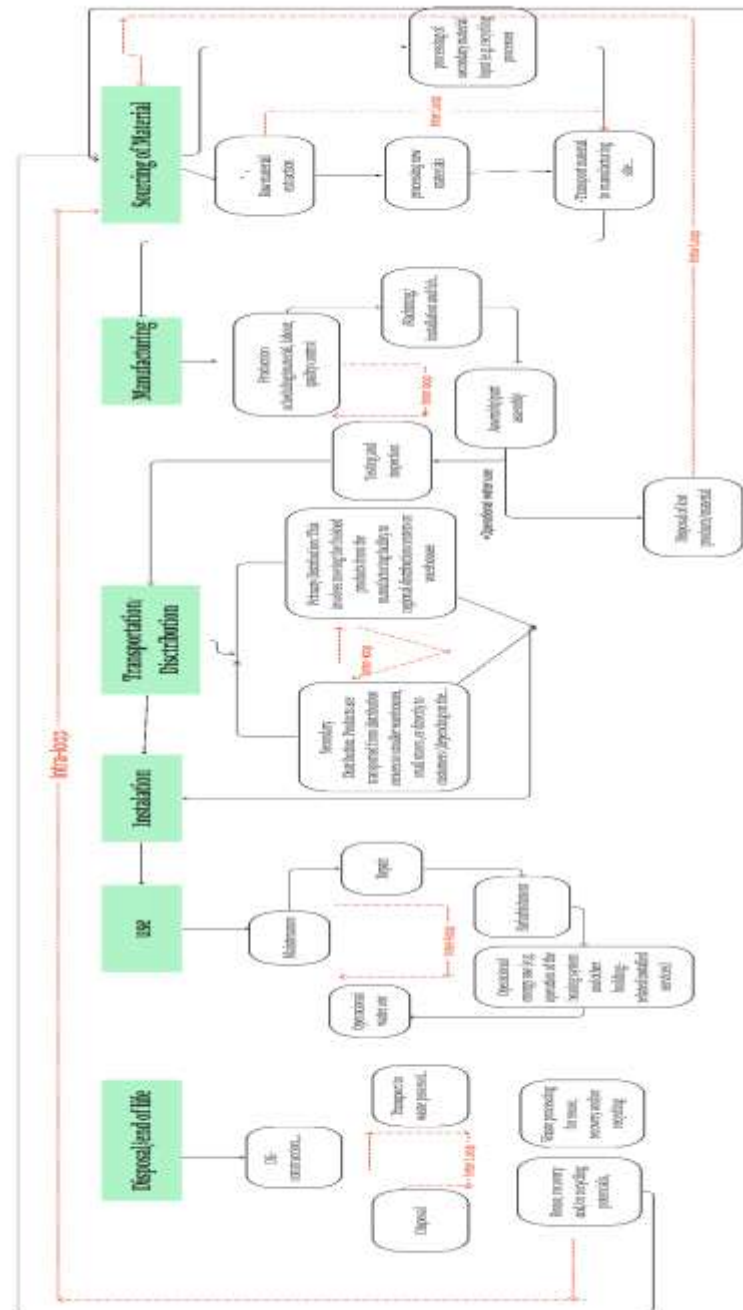


Fig. 1 Close loop frugal Product lifecycle strategy

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 [12]. 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. A lifecycle analysis from raw material to the end of life should be performed to identify the root causes of product failure at each life cycle stage [13]. Identifying root causes early and directly helps the designer's design decisions, reducing the need for redundant design refinements and testing.

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. Improving this feedback process is essential to improving resource use and reducing waste [14]. 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. 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.

3 Research Methodology

The study chose two cases (Tata Swach and Logitech–M215) for root cause analysis (RCA) that were initially meant to be examples of frugal design. However, while assessed using a frugal design evaluation model, both cases were determined to be non-frugal since they could not satisfy central frugality criteria [6]. To identify and address the causes of these failures in these cases, the study 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 [15]. As shown in Fig. 2, the following two-stage research method was adopted: 1) Scenario-based questionnaire survey, 2) Data Collection and result analysis



Fig. 2 Research Methodology

The study followed the methodology employed by Al-Zwainy (2013) to conduct the scenario-based questionnaire survey [16]. A multidisciplinary team of thirty engineering, manufacturing, construction, management, business, and sustainability experts was formed. These experts are working professionals in the firms chosen as a case for the study 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 [17]

4 Data Collection and Result Analysis

The study 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 [18]. 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 [19].

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, which helps to identify the root causes. The authors focus on the following RCA techniques [20].

Step 1: Ishikawa Diagram,

Step 2: Sub-cause prioritization

Step 3: Five-Why Method

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 [21].

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

1)The scenario-based survey was conducted (see Appendix I) 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 (substantial cost reduction, optimum performance level, and core functionality). 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. 3 shows a fishbone diagram displaying the sub-causes and thoroughly summarizes the primary and contributory factors.

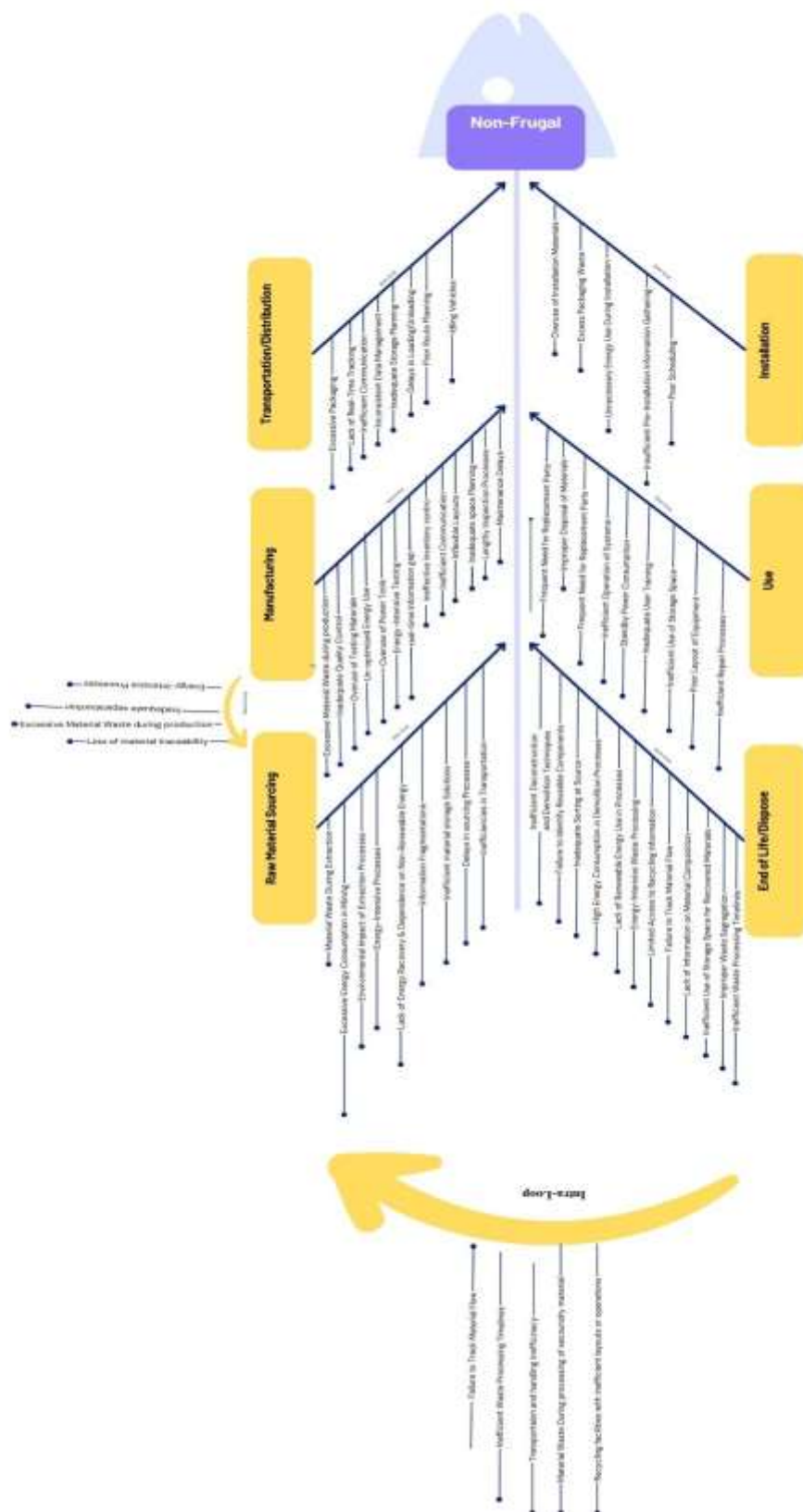


Fig. 3 Ishikawa diagram method

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 [22].

- **Impact assessment:** To assess how each sub-cause impacts the product's overall frugality, especially concerning frugality criteria [23].
- **Frequency analysis:** To determine the frequency of each sub-cause, either at various phases of the inter-loop or intra-loop frugal product lifecycle [24].
- **Cost-benefit analysis:** To determine if the anticipated benefits of addressing each sub-cause balance the costs [25].
- **Risk Assessment:** To assess the risks connected with each sub-cause, mainly if left unresolved [26].

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 [27].

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 1. The ratio of the random index (RI) to the consistency index (CI) is known as the consistency ratio (CR), see equations 1 and 2. Higher CR implies poor data quality. A CR value of less than 0.1 (10%) is generally desirable.

$$CR = \frac{CI}{RI} \quad (1)$$

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (2)$$

where $\lambda_{\max}$ denotes the matrix's highest eigenvalue

Table 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, $CR \ll 0.01$ (Standard consistency ratio), the Matrix is consistent, and the priority of factors was determined and weighted with the help of the AHP method. Table 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 2 Weightage of prioritization factors

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

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 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 Tables 3 and 4.

$$\text{Priority}[A] = \text{Average}(\text{weight}(\text{Impact assessment} * \text{Frequency Analysis} * \text{Cost-benefits} * \text{Risk Assessment}))$$

3

The study 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."

$$\text{priority} = \begin{cases} \text{low} & \text{if } 1.0 \leq 2.5 \\ \text{medium} & \text{if } 2.6 \leq 3.5 \\ \text{High} & \text{if } 3.6 \leq 5.0 \end{cases} \quad 4$$

Table 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 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 a 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 is in the 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 deconstruction 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 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.

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, the number "five" in the "5 Whys" technique is purely arbitrary [28].

The fishbone diagram can incorporate the five-why analysis technique or 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 study 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 Fig. 4,5,6,7, and 8). The following are the most crucial problems and root causes that lead to the failure of frugal design:

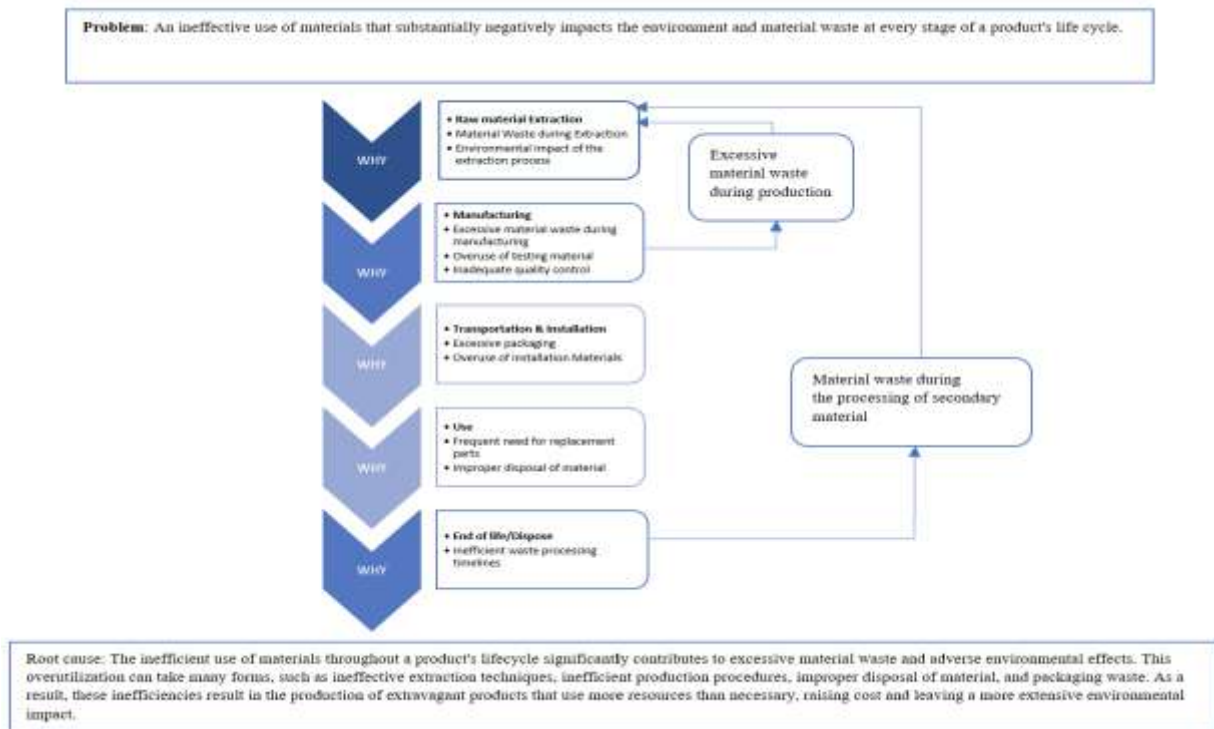


Fig. 4 Five-Why Methods for material relation problems

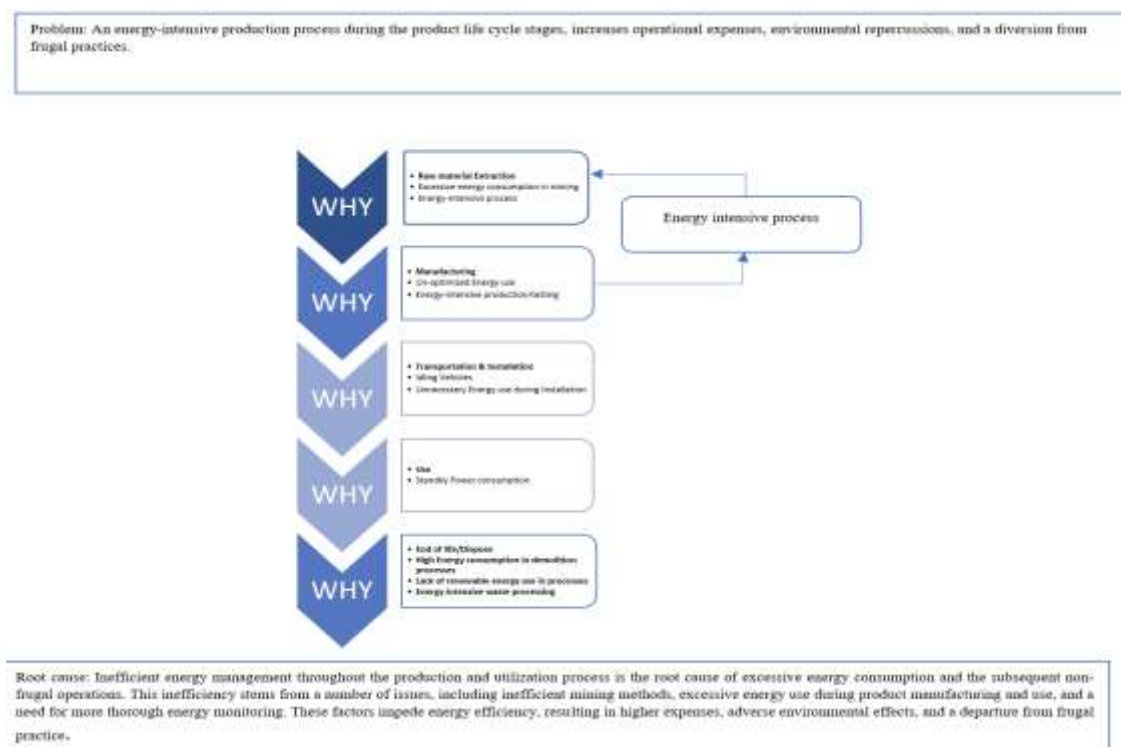
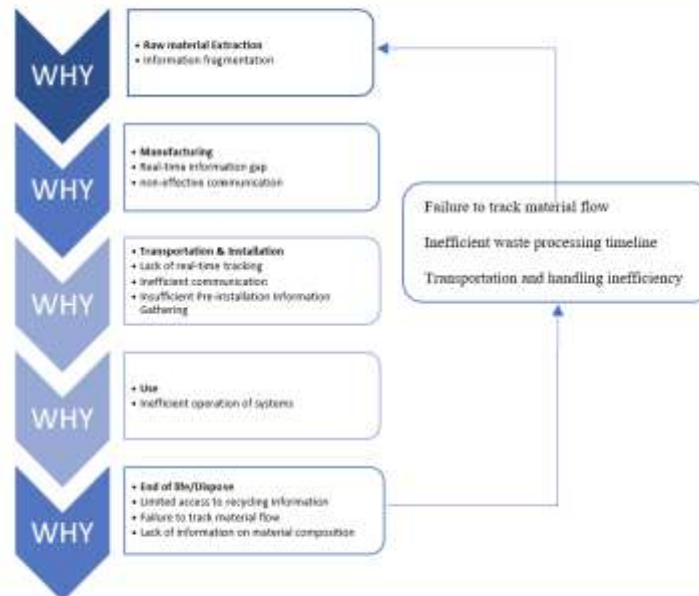


Fig. 5 Five-Why Methods for Energy-Related Problems

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 Five-Why Methods for Information Relational Problems

Problem: Significant operational issues are being caused by inefficient material handling and storage procedures. Higher expenses, squandered 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.



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. 7 Five-Why Methods for Space Relation Problems

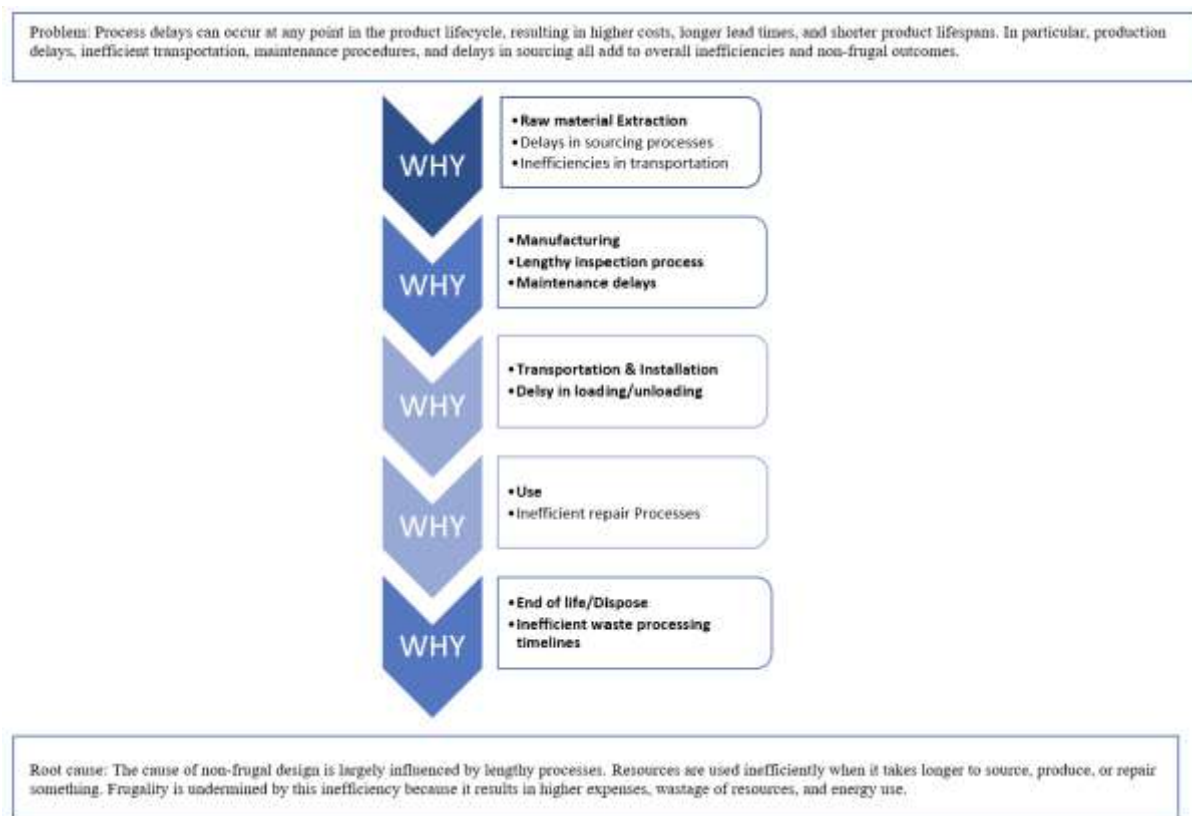


Fig. 8 Five-Why Methods for Time-Related Problems

The ineffective use of fundamental input resources (material, energy, information, space, and time) becomes a significant root cause of frugal design failure (see Table 5).

Table 5 Root cause analysis of frugal design failure

Problems	Root cause	Explanation
An ineffective use of materials that substantially negatively impacts the environment and results in material waste at every stage of a product's life cycle.	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 costs and leaving a more extensive environmental impact.	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
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 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	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.

	in higher expenses, adverse environmental effects, and a departure from frugal practice.	
Inadequate use and management of information, exemplified by fragmentation, poor communication, delayed tracking, and insufficient data collection during the product lifecycle, lead to non-frugal solutions, scheduling, rigid facility layouts, and a lack of storage space, 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 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.	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.	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 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 manufacturing 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.

The following are the root causes that led to the failure of frugal design in the chosen examples.

- **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, which 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:** The inability 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.

5 Conclusion

The study explicitly examined the root causes of frugal design failure through a closed-loop product lifecycle approach and developed root cause analysis (RCA) techniques, such as the Ishikawa diagram, prioritization, and the Five Whys method. By using these tools to analyze two cases of frugal design. The study revealed a complex network of 65 causes (56 inter-loop and 9 intra-loop) failures, of which 51 were ranked as most severe.

The results show that frugal design failure is primarily caused by the poor and suboptimal exploitation of material, energy, information, space, and time, which are the primary input resources that all underscore inefficiencies in the system of resource planning and management. Unless these inputs are managed efficiently throughout the whole product life cycle, they undermine the frugality criteria, i.e., significant cost savings, optimal performance level, and essential functionality.

These findings emphasize the imperative of a systematic and resource-effective design methodology factoring in the dynamic interaction of frugal design inputs at all stages of the lifecycle. Through the determination and ranking of the most important root causes for frugal design failure, this study provides practitioners and organizations with insightful directions for enhancing the success rate of frugal designs. Future studies should investigate adaptive and dynamic design paradigms that align input resource optimization better with the principles of frugal design. Eventually, solving these root causes is vital to further developing sustainable, inclusive, and high-performing products.

Data Availability Statement: The datasets created/analyzed during the current investigation are accessible from the corresponding author upon reasonable request.

Appendix

A. <https://docs.google.com/document/d/1f5FVd7FP7NR3JLgdSzHHN2FWrMt8aOHNGB1hi2Q9TXM/edit?usp=sharing>

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