JÖNKÖPING UNIVERSITY
School of Engineering

Refurbishment vs Remanufacturing: A comparative study.

Focus on Technological and Economic aspects in Industrial Production – General Perspective

FINAL REPORT

Main area: Production Systems

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This thesis is conducted at the School of Engineering at Jönköping University within production systems realization. The authors are responsible for the opinions, conclusions and results herein presented.

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Table of Contents

Chapter 5: Discussion and Comparative Analysis..................... 44

Chapter 6: Conclusion and Recommendations......................... 48

Reference 52

Abstract

This thesis investigates the critical techno-economic dimensions of refurbishment and remanufacturing processes within the context of industrial circularity. With the ever-growing concerns over sustainability and maximizing resource efficiency, manufacturers are increasingly embracing known circular economy strategies in a bid to extend product lifecycles. While both refurbishment and remanufacturing, which are both parts of the sustainability framework aim to restore product functionality, they differ in scope, process complexity, and economic return. This study utilizes **Configurational Analysis** to synthesize existing industrial standards and empirical data, interrogating the divergence between these two frameworks across lenses of process complexity, quality assurance, and financial viability.

The findings suggest that while remanufacturing yields higher-quality outputs and long-term value thus its preference for higher valued and costly products, refurbishment offers cost-effective solutions in less regulated sectors. Technological innovations, such as automation and data-driven diagnostics, as well as the economic significance of the choices production organizations make are reshaping both frameworks, making them vital components of sustainable industrial strategies.

Keywords: Remanufacturing, Refurbishment, Circular Economy, Technological, Economic Analysis, ISO 59000, Value Retention, Industrial Sustainability, Decision-Support Framework.

Chapter 1: Introduction

The global industrial sector has continued to undergo a fundamental transition from a traditional linear 'take-make-dispose' model toward a restorative circular economy. This shift is driven by the urgent necessity to decouple economic growth from finite resource consumption while mitigating the environmental impact of industrial waste (Morseletto, 2020). Central to this transition is the optimization of Value Retention Processes (VRPs), which aim to extend the functional utility of products and components. Within the diverse landscape of circularity, two strategies—**Refurbishment** and **Remanufacturing**—have emerged as the primary 'inner-loop' mechanisms for preserving the embodied energy and material integrity of high-value industrial assets.

The strategic hierarchy for these interventions is frequently conceptualized through the **'10R' framework**, a taxonomical evolution of early waste management principles (Kirchherr et al., 2023). Initially formalized to redefine the role of circularity in overcoming linear inefficiencies, the 10R hierarchy provides a tiered prioritization of strategies ranging from 'Refuse' to 'Recover' based on their potential for resource preservation. While foundational studies established the environmental priority of these loops, the operational complexity of implementing the highest-value Rs—specifically remanufacturing—remains a significant challenge for modern production organizations. This research focuses on the techno-economic tension between these high-level strategies to determine their viability in a volatile global market.

Further in the section, mention and emphasis would be made on the study aims and objectives, with an overview of where attention is to be paid. The problem statement would then follow, where the need to compare the two highlighted processes in the identified areas of technology and economy would be highlighted. The scope of the thesis would be defined to give proper context, with the listing of the research questions. Lastly, the structure of which the thesis would follow would be detailed.

1. 1 Background

With the ever-increasing needs of man, comes the need for creating ways to satisfy them. These ways, however, have continuously been improved upon and currently, only ways which are most environmentally friendly are prioritized. With the rapid development of the economy, social resources have become increasingly depleted (Cao et al., 2020). There is more attention being paid to ensuring a more sustainable and circular approach towards production and many industries are beginning to embrace this or at least are being encouraged to embrace this.

Several factors have led to an increase in the focus on sustainable development. In this context, the concept of Circular Economy (CE) has gained tremendous momentum in research and implementation. Fitted into CE's concept, the Life Extension Strategies (LES) have been popular among industrial practitioners, regulators, policymakers, and academics from different industries due to the several benefits of these strategies (C. Ferreira, G. Gonçalves 2021).

Industrial organizations have started embracing the 10R strategy framework; Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose Recycle and Recover in their production processes. These ten strategies guarantee avoiding the creation of waste, encourage maximizing material usage, and extending the lifespan of materials. These are possible strategies embraced to create product and resource circularity.

In the current industrial landscape, the pursuit of a decoupled, low-carbon economy has transitioned from a peripheral corporate social responsibility (CSR) goal to a core strategic mandate (Morseletto, 2020; Sehnem et al., 2022). Global manufacturers are currently operating under unprecedented pressure from transnational regulatory frameworks, such as the European Union’s Circular Economy Action Plan (CEAP) and the subsequent Ecodesign for Sustainable Products Regulation (ESPR), which mandate significant increases in product durability, reparability, and recycled content (European Commission, 2022; Sönnichsen & Clement, 2020). While foundational institutions like the National Center for Remanufacturing and Resource Recovery (NC3R) in the United States established the early technical parameters for resource recovery as far back as 1990, the modern era is characterized by a shift toward mandatory Extended Producer Responsibility (EPR) and the 'Right to Repair' movement (Hernandez et al., 2020). This shift forces a transition from voluntary recycling to high-value circularity strategies—namely refurbishment and remanufacturing—as primary vehicles for achieving the net-zero targets outlined in the 2021-2026 industrial policies (Velenturf & Purnell, 2021).

Within this framework, refurbishment and remanufacturing have emerged as two vital strategies to extend product lifespans and close resource loops (European Commission, 2020). These two are under the spotlight for the purpose of this study.

Though as stated above, the two processes seek to reintroduce value to products that have reached their end-of-life, they differ significantly in various ways, be it in scope, technology of process and economic implications. The two terms have been described differently. Refurbishment involves repairing or fixing faulty select components of a used product to enable it function again, often with minimal disassembly. In contrast, remanufacturing is synthesized as an industrial grade 'Inner Loop' strategy that transcends basic repair or reconditioning. It is a comprehensive, standardized process involving Complete Knock Down (CKD) disassembly to the component level, followed by rigorous cleaning and Non-Destructive Testing (NDT) to identify latent fatigue (ISO 59010, 2024). Also, refurbishing involves restoring an old product and updating it to meet modern standards. It aims to upgrade or modernize the product's functionality. It usually does not entail disassembly; instead, it focuses on replacing parts. On the other hand, Remanufacturing involves incorporating parts of discarded products into a new product with the same function. The process ensures that the remanufactured product attains the quality equivalent to a brand-new one, even when utilizing components retrieved or reclaimed from other products (Morseletto, 2020; Yuksek et al., 2023).

Aside from the descriptions given above, there are others which have been given by previous researchers describing the two concepts. In addition, there continues to be growing interest in embracing a more sustainable and circular manufacturing approach. However, there remains somewhat confusion, or better put lack of proper clarity among the players in the production industry about when and how to apply one versus the other. Modern remanufacturing now leverages Real-Time Condition Monitoring and big data analytics to predict core quality before disassembly, significantly reducing the financial risk of 'uncertain core yield' (Dev et al., 2020). From the description of the two processes, a clear difference in the activities involved in them has been established. In selecting the method of extending the lifecycle of a product, many factors come into consideration such as timeline, cost, availability of manpower, technology required for the process, economic impact both on the company and of course on the final customers. This thesis aims to address the complex relationship that exists between the two frameworks, focusing on their technological and economic factors within industrial production.

1.2 Problem Statement

A sustainable and circular approach towards production has been on the increase in recent times. Production companies globally now look for the best way to manage waste yet create the desired values expected in the product. While the '10R' hierarchy remains the definitive framework for ranking resource value retention (Kirchherr et al., 2023), the operational boundaries between refurbishment and remanufacturing have historically been characterized by taxonomic ambiguity (Morseletto, 2020; Reike et al., 2023). However, the synthesis indicates that this 'application confusion' is currently being mitigated by the global rollout of the ISO 59000:2024 series, which provides the first unified international criteria for distinguishing between 'Functional Restoration' and 'Zero-Fatigue Reconstruction' (ISO, 2024). Despite these advancements, a strategic gap persists in industrial practice; firms frequently struggle to align their technical capabilities with the specific regulatory requirements of these standards. This research argues that the perceived confusion is no longer just a linguistic issue, but a Socio-Technical misalignment where the economic drive for speed (Refurbishment) conflicts with the standard-driven mandate for integrity (Remanufacturing) (Sönnichsen & Clement, 2020).

First is the concern about the inter usage of the definitions. Since both are options available for the extension of the life span of a product, there is often an overlap in their definitions. This definitional overlap creates a state of Information Asymmetry that fundamentally undermines market confidence in recovered assets (Charnley et al., 2022). The synthesis suggests that when the technical boundaries between 'as-new' remanufacturing and 'functional' refurbishment remain blurred, end-users face a significant **Perceived Risk** regarding the actual residual value and the reliable life-extension of the product (Long et al., 2021). This uncertainty is no longer merely a consumer-perception issue but a structural barrier to the **Circular Transition**; without standardized verification, the 'Trust-Price Linkage' collapses, as buyers cannot differentiate between a product that has undergone zero-fatigue reconstruction and one that has merely received cosmetic repair (Sönnichsen & Clement, 2020). Consequently, addressing this ambiguity via the **ISO 59000 (2024)** framework is essential for derisking circular investments and ensuring that the economic value of life-extended products is accurately captured and communicated (Velenturf & Purnell, 2021).

To their disposal are an option of strategies to pick from, however making the right choice from these varieties possess its own challenges, majorly because of the lack of clarity in the distinctions amongst these options, specifically between refurbishment and remanufacturing that are under focus for this thesis. From the varying complexities involved in the technological processes across the different levels of production, to the expected economic returns from investments made on product type, meeting market demands to satisfying regulatory conditions, key stakeholders saddled with the responsibilities to make key decisions are expected to make detailed comparative analyses to arrive at empirical decisions on which their choices can be based. This thesis aims to provide data driven by empirical analyses of already existing research work and industry practices.

We can agree that both strategies aim to retain product value and extend their life cycle, they involve a significant variance in the levels of disassembly, part selection and replacement, testing and most significantly final product quality. (Amaitik et al., 2022; Canon Europe, 2021).

This study attempts to aid in clarifying the ambiguity mentioned above and come up with criteria-based approach that compares the two strategies. This study will aim to achieve this by focusing on two criteria: the technological and economic criteria.

1. Technological Criteria: How do we determine the superiority of one of the strategies based on some technological characteristics such as product design, testing strategies available, cleaning techniques, engineering and re-engineering, to mention a few?
2. Economic Criteria: Are there trade-offs that can be quantified when comparisons are made between the high up-front capital investments of remanufacturing against the lower investment costs seen in refurbishment? These tradeoffs shall be assessed against key performance indicators such as life cycle cost, amount of value retained (with respect to the original product) and the acceptance of the rebirthed product.

While academic discourse often treats refurbishment and remanufacturing as a spectrum of 'Value Retention Processes' (VRPs) (International Resource Panel [IRP], 2018; Kurilova-Palisaitiene et al., 2021), this study recognizes that in a practical industrial setting, the distinction is governed by rigorous industry standards. To ensure a robust comparative analysis, this research moves beyond conceptual definitions to utilize international benchmarks—specifically the **BS 8887** series and relevant **ISO** quality frameworks—as the primary lenses for evaluation (British Standards Institution [BSI], 2010).

Integrating these standards is essential for two reasons. Technically, they define the 'as-new' performance requirements and full disassembly protocols that separate a remanufactured product from a refurbished one, which typically focuses on functional restoration to 'working order' (Beneduce et al., 2024; BSI, 2010). Economically, these standards dictate the total cost of certification, the legal weight of mandatory warranty obligations, and the final market value of the restored asset (Choudhary et al., 2023; Nasr, 2021). This ensures that the price premium associated with 'as-new' performance is protected by a formalized regulatory framework rather than subjective market perception. By anchoring the technological and economic comparison on these established industry protocols, this thesis provides a standardized framework applicable across general industrial production settings, ensuring that the findings align with global manufacturing best practices.

To conclude this problem statement, approaching this thesis from these technology and economic dimensions, will aim to provide evidence-based outcomes specifically to guide decision making by key stakeholders in industrial set ups. It will show a comparative study that clearly states the operational processes involved in both strategies and defines the boundaries that exist among the two of them.

1.3 Purpose, Objectives and Research Questions

1.3.1 Research Purpose

The purpose of this work is to critically compare refurbishment and remanufacturing in industrial production to identify their advantages and disadvantages, possible limitations and how suitable they can be for various industrial applications with focus on the technological processes. It will be specific in the analysis of how the cost-effectiveness of one compare to the other, the outcome of comparing resource consumption, technical requirements, customer and market acceptance for the two frameworks.

1.3.2 Research Objectives

This thesis aims to conduct a comparative analysis of refurbishment and remanufacturing in industrial production. To achieve this, the study has as its objectives the following which would serve as guide:

1. To simplify the definition of refurbishment and remanufacturing, within the context of a circular industrial production system
2. Identify and assess the technological steps, standards and tools involved in both frameworks,
3. Evaluate the economic impact of both frameworks when analyses are done on their cost and value implications.
4. To provide empirical recommendations for organizations who wish to embrace any or both frameworks to make guided decisions on the best approach for their end-of-life product optimization strategies and approach.
5. To evaluate the technological pathways against international industrial standards (BS 8887/ISO 59000).

1.3.3 Research Questions

While the objectives listed above define the goals of this study, the research is fundamentally driven by the need to answer specific inquiries regarding the current industrial landscape. As a result, this thesis seeks to address the following Research Questions:

1. What are the major differences in the applied technology between refurbishment and remanufacturing processes for an industrial production setup?
2. What are the comparative differences between refurbishment and remanufacturing when compared economically in the areas of cost efficiency, investment, and profitability?
3. What are the gains of selecting one of the two identified frameworks over the other in sustaining industrial circular economy?

The first research question sets the precedence before comparisons can commence. Since this thesis is focusing on the technological and economic aspects of comparing the two frameworks, it would be good to know and list the technological implications of one over the other. A proper understanding of the technical approaches used by either process would form a basis for comparisons. Industrial manufacturers would have adequate information about the process that best fits extending the life of their product, and this would aid the right decision to be made.

The second research question would answer the question of the economic relevance of refurbishment and remanufacturing. It will show the terms to base the comparisons, such as the cost efficiency of both processes, profitability when measured against the lifecycle of the product.

Lastly, the third research question would seek to bring the first two questions together and list the technological and economic gains and disadvantages of refurbishment and remanufacturing. With this, industrial companies would have data to make the right choice of which framework best suits their product from the technological and economic point of view.

1.4 Scope and Delimitations

The focus for this thesis would be on industrial production of sectors where refurbishment and remanufacturing find common usage. This would help to give perspective and to ensure that the basis of comparison is balanced and not in favor of either of the identified sustainability process under consideration.

This study adopts a structured qualitative comparative approach: qualitative comparative analysis (QCA) methodology is used to filter out information within the framework of a purposive documentary review (PDR), and as such it is limited to the already existing body of knowledge. This means that there would be no collection of data through any of the known means such as surveys, interviews. Data would be gotten from technical reports, academic journals, and similar sources. Attention would be to the differences or similarities in the two sustainability processes for industrial production with a focus on a specific industry at each time. All analysis would be focused on the technological process and economic implications, however, mentions of other relevant areas would be made only when necessary.

The contribution of this study extends beyond the usual addition to literature. By synthesizing disparate technological and economic data, this research seeks to establish a prescriptive decision-support framework—the Configurational EoL Strategy Model (CESM). This model serves as a functional bridge between theoretical circular economy principles and industrial application, providing stakeholders with the necessary logic to optimize value retention. Furthermore, by addressing the documented scarcity of comparative studies between refurbishment and remanufacturing, this work sets a new methodological benchmark for evaluating Value Retention Processes (VRPs) in high-value industrial sectors.

1.5 Principal Contribution of the Thesis.

This thesis aims to connect the dots that can be found in existing literature by moving beyond the simple comparison of refurbishment and remanufacturing processes to provide an integrated framework to support decision. The thesis delivers two principal contributions to both academic theory and economical and industrial practice.

1. Academic Contribution: Configurational End-of-Life (EoL) Strategy Model

This study introduces the Configurational EoL Strategy Model (CESM). The CESM is a theoretical output extracted from the filtering of information contained in literature using the principles of Qualitative Comparative Analysis (QCA).

The structural architecture of this research is informed by the principles of Qualitative Comparative Analysis (QCA), which is uniquely suited for investigating the causal complexity inherent in circular transitions (Pappas & Woodside, 2021).

It supports the narrative that the optimal selection between refurbishment and remanufacturing is rarely determined by a single factor (e.g., cost or technology) but rather by the simultaneous presence of specific technological and economic conditions (configurational). This approach moves the field away from linear decision-making models towards a more nuanced, systemic understanding of value retention in the circular economy (CE).

2. Practical Contribution: Prescriptive Decision-Support Matrix

Another output from this thesis work is a **Techno-Economic Decision-Support Matrix** (derived from Technological and economical). This matrix directly addresses the core research questions by serving as a tool for industrial stakeholders and service managers. By providing an evidence-based method, the matrix enables users to quickly identify the characteristics that maximize profitability and resource efficiency for a specific industrial asset class. The resulting framework provides a clear, prescriptive guide for strategic investment and decision-making regarding the lifecycle trajectory of End-of-Life (EoL) products. This approach aligns with the contemporary mandate for **Evidence-Based Management (EBM)**, which necessitates that industrial transitions be grounded in high-quality, synthesized data rather than anecdotal intuition (**Sassanelli & Terzi, 2024; Oghazi et al., 2023**). In a circular context, this shift ensures that End-of-Life decisions are based on measurable engineering benchmarks and standardized economic thresholds.

1.6 Structure of the Thesis.

The structure of the thesis is found on the table of contents. Efforts have been made to list them in a manner that would aid the ease and flow of reading.

A pictorial representation of this structure is depicted in Fig 1. Structure of the Thesis below:

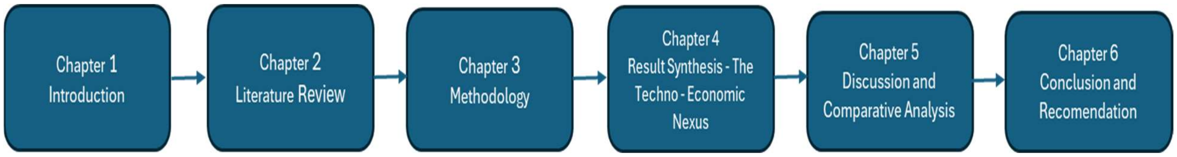

Fig 1. Structure of the Thesis

1.6.1 Research Rationale.

This thesis is structured into eight distinct yet interrelated chapters, systematically designed to address the research objectives through a multi-disciplinary lens.

Chapter 1: Introduction establishes the foundational context of the study, delineating the problem statement and the necessitating drivers for a comparative analysis of circular frameworks. It articulates the core research questions and defines the scope and limitations of the investigation.

Chapter 2: Literature Review and Theoretical Framework provide a critical synthesis of existing scholarship. This chapter goes beyond a summary to interrogate the technological and economic intersections of circularity, identifying significant knowledge gaps and establishing the theoretical basis for the subsequent analysis.

Chapter 3: Methodology details the research design and the application of Qualitative Comparative Analysis (QCA). It provides a rigorous account of the inclusion and exclusion criteria, data collection protocols, ethical considerations, and the methodological constraints inherent in the study.

Chapters 4: Results Synthesis – The Tecno-Economic Nexus comprise the empirical core of the report. It focuses on the technological variables and process flows and examines the corresponding economic implications. These chapter elucidate the operational mechanics of both refurbishment and remanufacturing.

Chapter 5: Comparative Analysis and Discussion integrate the preceding findings to identify points of agreement and disagreement between the two frameworks. It provides empirical evidence to determine the strategic advantages of each approach within specific industrial contexts.

Chapter 6: Conclusion and Recommendations culminate the research by distilling key insights and offering prescriptive recommendations for industrial application. The thesis concludes with a discussion on the broader implications for circular economy policy and suggestions for future scholarly inquiry.

Chapter 2: Literature Review

2.1 Introduction

Every organization involved in industrial production has a common target. This is to satisfy their customers' needs. However, there has become a growing interest in reducing waste, remaining competitive and maximizing cost effectiveness while doing this. Modern industrial sustainability is defined by the systemic integration of resource efficiency, value retention, and regenerative design (Morseletto, 2020). Rather than simple waste mitigation, being 'sustainable' in the current decade involves operationalizing the Circular Economy (CE) to ensure that economic development is decoupled from environmental impact (Velenturf & Purnell, 2021). Consequently, refurbishment and remanufacturing serve as critical sustainability levers by maintaining product utility at its highest value, thereby satisfying market demand while adhering to the 'planetary boundaries' framework and the latest ESG (Environmental, Social, and Governance) reporting mandates (Reike et al., 2023).

To operationalize sustainability, organizations adopt various frameworks that categorize Value Retention Processes (VRPs). While the 10R sustainability framework (Reike et al., 2023) provides a comprehensive theoretical hierarchy ranging from Refuse to Recover, its industrial application is best understood when aligned with globally recognized standards.

In practice, international standards such as ISO 59004:2024 and BS 8887-220 provide the technical requirements for 'Design for Resilient End-of-Life.' These standards move beyond theoretical 'Rs' to define specific engineering protocols for refurbishment and remanufacturing. For instance, the United Nations Environment Programme (UNEP, 2020) identifies remanufacturing and refurbishment as the two most critical VRPs for high-value industrial equipment, citing their adoption by multinational firms like Caterpillar and Cummins to achieve up to 80% material savings (Nasr, 2021).

Therefore, this study utilizes the 10R framework merely as a taxonomic guide, while primarily focusing on the technological and economic procedures mandated by the ISO 55001 Asset Management standards and the European Green Deal's Circular Economy Action Plan.

This literature review isn't just a summary of what has been said before; it is a critical look at the current state of refurbishment and remanufacturing. The objective of this section is to build a solid foundation for the study by clearing up the conceptual overlap between these two strategies, specifically by looking at them through both a technical and an economic lens.

In the following sections, there is highlight of the clear benefits of these frameworks while also pointing out the specific knowledge gaps that still exist. These gaps are exactly why this study is necessary. To keep the findings relevant to today's industrial climate, the study has focused on academic, industrial, and policy-based literature published between 2000 and 2026. This timeframe was chosen to bridge the gap between foundational circular theory and the most recent shifts in global standards and technology.

To ensure the quality of this data, there was emphasis on the sources ensuring they were from established databases like Google Scholar, ScienceDirect, Scopus, and SpringerLink. These platforms were selected because they offer the most comprehensive, peer-reviewed coverage of sustainability and industrial engineering, providing the rigorous evidence-based needed to support the arguments in this report. Though this is detailed more in the methodology chapter, it was worth being mentioned here.

2.2 Evolving Definitions of Value Retention Frameworks

It is fundamentally important to understand the key terms; refurbishment and remanufacturing- as this would aid the differentiation of the technical process, economic and environmental involved in industrial production. The academic and industrial understanding of refurbishment and remanufacturing has undergone a paradigm shift in the last five years, moving from simple repair-based definitions to complex Value Retention Processes (VRPs).

2.2.1 Refurbishment:

Contemporary literature defines refurbishment as a "mid-loop" circular strategy focusing on the functional and aesthetic restoration of products. Unlike earlier definitions which viewed it as mere cleaning, recent studies by **Morseletto (2020)** and **Borg et al. (2021)** characterize it as a "diagnostic-led intervention." It is strategically deployed in high-velocity sectors like consumer electronics where "perceived obsolescence" occurs quickly. The technical hallmark of modern refurbishment is its reliance on selective disassembly—targeting only the primary failure points to minimize labor costs while extending the product's usable life by approximately 30–50% (Reike et al., 2023)

This involves restoring an old product and updating it to meet modern standards. It aims to upgrade or modernize the product's functionality. Technically, refurbishment is characterized by a 'minimal intervention' approach. Unlike remanufacturing, it typically avoids a total teardown of the product; instead, it utilizes **selective disassembly** to target and replace only those components that have failed or reached their wear limit (Morseletto, 2020; Reike et al., 2023). This focused method allows for functional restoration without the high labor costs and energy expenditure required for a full industrial re-engineering (Borg et al., 2021).

2.2.2 Remanufacturing:

In contrast, remanufacturing is now defined as an "industrial-scale restorative process" that guarantees "as-new" performance. The distinction is no longer just the quality of the result, but the **standardization of the workflow**. According to **Nasr (2021)** and the **ISO 59000:2024 protocols**, remanufacturing is an integrated manufacturing stage where the 'core' is treated as a raw material. Recent in-depth analyses highlight that remanufacturing is not just about "fixing," but about "re-engineering" the product to current or even upgraded specifications, often involving additive manufacturing and automated inspection (Kerin & Pham, 2020). This rigorous adherence to Original Equipment Manufacturer (OEM) tolerances is what separates it from all other circular strategies.

Remanufacturing ensures the product attains the quality equivalent to a brand-new one, even when utilizing components retrieved or reclaimed from other products (Morseletto, 2020; Yuksek et al., 2023).

2.2.3 Defining the Conceptual Landscape: Related Terms

Due to their similarity of purpose, which is to extend the life cycle of a product, it is common to see several related terms used alongside them. In many industrial circles, terms like repair, reconditioning, reuse, and recycling are often used interchangeably.

However, the literature indicates that the accuracy of these terms depends heavily on the specific technical context they are applied to.

For instance, **Repair** is usually a localized fix; it restores a specific function without the need for a full inspection or major component replacement. **Reconditioning** occupies the middle ground, offering a broader scope than a simple repair but falling short of a full refurbishment. On the other hand, **Reuse** is the simplest form of circularity, where an item is put back into service without any modifications at all. **Recycling** is fundamentally different from the others because it involves breaking the product down to its raw materials for reprocessing.

In contrast, this study focuses on refurbishment and remanufacturing because they are far more efficient at preserving the product's original structure and "embodied energy" (UNEP, 2021). By keeping the product's high-value components intact rather than melting them down, these strategies represent the most effective forms of **Product Life Extension (PLE)**. They don't just support sustainable consumption; they maximize the actual utility we get from every manufactured good, aligning perfectly with the latest global circularity standards (ISO 59004, 2024).

2.3 The Normative Framework: Industry Standards and Regulatory Definitions

While the previous sections help us understand the concepts of refurbishment and remanufacturing, academic theory alone often lacks the precision needed for actual industrial work. In the real world, the line between these two strategies isn't just about how much work is done; it is defined by strict international standards that dictate everything from how a part is tested to who is legally liable if it fails.

In a practical production setting, moving from refurbishment to remanufacturing isn't just a "step up"—it's a move into a different level of compliance and protocol. To make this distinction clear, Table 2.1 below synthesizes the core requirements from **BS 8887-220** and the **ISO 59000** series to establish the evaluative framework for this study.

Table 2.1 *Comparative Analysis of Refurbishment and Remanufacturing Based on Industry Standards.*

Feature	Refurbishment (Standardized View)	Remanufacturing (Standardized View)	Primary Standard Ref.

Operational Definition	Functional restoration of a product to a "working order" state.	Systematic process to return a product to "as-new" or "better" performance.	BS 8887-220:2010
Disassembly Level	Partial; focused only on failed or worn components.	Full; product is stripped down to the "core" (individual parts).	ISO 59010:2024
Quality Assurance	Tested for functionality and safety (e.g., CE Marking).	Must meet or exceed Original Equipment Manufacturer (OEM) specs.	ISO 9001:2015
Warranty Requirement	Variable; usually limited to the repaired parts or 3–6 months.	Mandatory; must be equivalent to a new product warranty.	BS 8887-220
Economic Value	Low to Moderate (30–50% of new price).	High (60–80% of new price) due to certified quality.	IRP (2018)
End-of-Life Status	Life extension (Temporary).	Second Life / New Cycle (Sustainable).	ISO 14001 / ISO 59000

2.4 Technological Dimensions of Refurbishment and Remanufacturing

The transition from a linear 'take-make-waste' model to a circular industrial system relies heavily on the technical maturity of Value Retention Processes (VRPs). Central to this transition is the technological distinction between refurbishment and remanufacturing, which is no longer viewed merely as a difference in "cleaning" or "repairing," but as a fundamental divergence in engineering depth (Reike et al., 2023). While the literature often groups these strategies under the umbrella of 'circularity,' recent industrial shifts emphasize that the technological requirements for each are dictated by the complexity of the product architecture and the availability of technical data, such as Digital Product Passports (DPPs) (European Commission, 2024).

Understanding these dimensions is critical because the choice between refurbishment and remanufacturing determines the total lifecycle energy consumption and the precision of the restoration process. To provide a rigorous technological comparison, this section evaluates the literature across three critical pillars: the **standardized process flows** required for industrial-scale operations, the **technological bottlenecks**—such as core uncertainty and disassembly complexity—that impede scaling, and finally, the **reliability and quality assurance metrics** that define the marketability of the restored product (Saccani et al., 2020; ISO 59010, 2024). By analyzing these dimensions, the study establishes the technical baseline necessary to support the subsequent economic analysis.

2.4.1 Refurbishment and Remanufacturing Process Flow:

Refurbishment and Remanufacturing are two of the frameworks employed in the recovery of used products. In both processes exist steps which differentiate one from the other. These steps can be comparatively seen more in the table as shown below.

Table 2.*2 Comparison between Refurbishment and Re-manufacturing Concepts*

Operational Step	**Refurbishment**	**Remanufacturing**
Core Input Inspection	Visual inspection and diagnostic testing (focus on identifying failures)	Total disassembly of the product into core components
Disassembly Extent	Partial disassembly (limited to failed sub-assemblies)	Total cleaning and detailed inspection of **each** part
Component Intervention	Repair of identified faulty components	Restoration of components to meet original specifications
Aesthetic Restoration	Optical improvements such as repainting, polishing	Precise reassembly, using specific tools and adherence to strict tolerances
Final Quality Assurance	Functionality testing and repackaging (focus on operational capacity)	Full performance testing and **quality certification** before repackaging (focus on 'like-new' reliability)

When we look at the actual shop-floor requirements, the difference comes down to the depth of the intervention. In remanufacturing, the degree of disassembly, the intensity of the inspections, and the rigor of the testing all reflect one specific goal: restoring the product to a 'like-new' or 'zero-hour' state. In contrast, refurbishment is a more targeted approach. It prioritizes getting the product back to operational functionality rather than trying to meet the original factory standards (UNEP, 2021; ISO 59010, 2024).

2.4.2 Technological and Operational Barriers Setbacks:

Despite the clear benefits of these recovery strategies, significant technological hurdles often prevent their widespread adoption. In this literature review, the identified setbacks are not merely logistical but are rooted in the complex "technological dimensions" of modern manufacturing. These barriers often dictate whether a product is even a candidate for remanufacturing or if it must be relegated to a lower-value recovery loop.

1. Product Design and "Design for Disassembly" (DfD) Complexity A primary setback is that many modern industrial products are not designed with end-of-life recovery in mind. The use of permanent joining techniques, such as adhesives or welding, complicates the "Complete Knock-Down" (CKD) required for remanufacturing. Research suggests that without **Design for Disassembly (DfD)** principles being applied at the OEM stage, the labor costs and the physical risk of component damage during recovery often become deal-breakers (**Zhang et al., 2021; Umeda et al., 2024**). In a modern production setting, if a product is not designed to be taken apart easily, the cost of the manual labor required usually outweighs the value of the materials being saved.

2. The "Uncertainty of Core Quality" Unlike traditional manufacturing, where raw materials are predictable, remanufacturers deal with "cores" (used products) of unknown quality. Technological advancements in Non-Destructive Testing (NDT)—such as AI-enhanced ultrasonic scanning—have tried to bridge this information gap. However, accurately predicting the 'residual fatigue life' of a component remains a significant technical headache (Liu et al., 2023; Zheng et al., 2024). Even with modern sensors, determining exactly how much 'work' a used part can still do is a complex calculation that continues to challenge the industry's ability to guarantee 'as-new' performance. This uncertainty often forces a conservative—and expensive—approach to testing and inspection (Zheng et al., 2021).

3. Cleaning and Surface Engineering Constraints The technological dimension of "cleaning" is often overlooked but represents a significant setback. Removing industrial contaminants without damaging the underlying substrate requires advanced chemical and laser cleaning technologies. The review of current literature indicates that the environmental and technical costs of these cleaning processes can often outweigh the benefits if the product's material composition is not compatible with modern restoration techniques (Garrido-Hidalgo et al., 2020).

4. Data Information Gaps (Digital Thread): A final barrier is the chronic lack of reliable data. Without a clear "Product Life Cycle" record—knowing exactly how many hours a product ran, or the heat levels it endured—remanufacturers are essentially forced to guess the level of internal wear. While current research into **Digital Twins**

and **IoT tracking** offers a glimpse into a more transparent future, this information gap remains a critical bottleneck for the millions of legacy products currently in the field (Kerin & Pham, 2020).

2.4.3 Quality of the finished product:

The quality and level of reliance on the functional qualities of the final product differ between refurbishment and remanufacturing. While refurbished products meet the basic operational requirements in most cases, they do not meet the original performance standards. This has implications such as a higher risk of failure. Also, companies who produce refurbished products offer limited warranties if they even offer at all. Refurbishment is favoured for markets where cost sensitivity is to be given priority over negligible performance trade-offs.

As for remanufactured products, they are restored to meet or exceed OEM standards. This is often accompanied by extended warranties, rigorous testing, and third-party certifications, especially in sectors such as aerospace and automotive (Sutherland et al., 2008). This higher performance outcome makes it applicability more suitable in industries where there are higher emphases on reliability.

2.5 Economic Perspectives

While the technological differences are clear, the real decision-making usually happens at the balance sheet level. Although refurbishment and remanufacturing share the goal of lifecycle extension, their economic viability is driven by very different cost-benefit architectures. In today’s market—defined by volatile material costs and strict ESG (Environmental, Social, and Governance) mandates—these aren't just "green" initiatives anymore; they are essential strategies for protecting industrial margins (Bressanelli et al., 2022).

2.5.1 Cost Structures and Operational Economics

The financial entry barrier for refurbishment is significantly lower than for remanufacturing, primarily because the Capital Expenditure (CAPEX) requirements are lighter. Because refurbishment follows a 'minimal intervention' model, it focuses on quick functional fixes rather than a total system overhaul. As Choudhary et al. (2023) point out, this makes it the ideal choice for SMEs and third-party resellers who need to move inventory quickly without heavy upfront investment.

In contrast, remanufacturing is a much larger industrial commitment. It requires the infrastructure to handle a full 'Complete Knock Down' (CKD) process, which naturally drives up labor and technology costs. However, the payoff is in the Value Retention (VR). In the heavy machinery sector, for example, firms like Caterpillar have shown that remanufacturing can slash production costs by 40% to 50% compared to new builds, while still maintaining high-end margins (Nasr, 2021). My analysis suggests that while remanufacturing has a higher break-even point, it offers much better long-term profitability for high-value assets where the 'core' is still structurally sound.

2.5.2 Value Recovery and Asset Utilization

Modern economic frameworks now distinguish these processes by their **Revenue-per-Unit** potential. Refurbishment is a volume-driven game. We see this clearly in the consumer electronics sector, where the secondary market for smartphones is growing faster than new sales (Borg et al., 2021). Here, the economic "win" is speed; firms can capture the budget-conscious market without the deep technical costs of a full remanufacture.

Remanufacturing, however, is increasingly moving toward **Product-Service Systems (PSS)** and 'Circular Subscription' models (Tukker, 2023). In these scenarios, the manufacturer keeps ownership of the asset, and the value is extracted through multiple remanufacturing loops. This shift from 'selling a product' to 'selling performance' provides a steady revenue stream and acts as a buffer against material price shocks—a major advantage recently observed in the aerospace and medical sectors (Kurdve & Bellgran, 2021).

2.5.3 Market Acceptance and Consumer Perception

Ultimately, the 'Economic Gap' between these strategies often comes down to **Consumer Perceived Value (CPV)**. Market data indicates a clear 'Quality Premium' for remanufactured goods; because they often carry warranties identical to new products, they can be priced at 60-80% of the original retail price (Kerin & Pham, 2020).

Refurbished products, on the other hand, face more 'Lemons Market' risk, where inconsistent quality can drag down prices. However, I’ve noticed that 'Certified Refurbishment' programs (like those from Apple or Dell) are beginning to change this. By using formal certification to build trust, these firms are proving that the economic success of refurbishment is often less about the technology and more about the branding ecosystem surrounding the product (Hazvee et al., 2022).

To show how these dynamics play out in the real world, Table 2.3 below summarizes synthesized cases highlighting how global leaders choose their strategies based on asset value and market demand.

Table 2.3 *Comparative Economic Case Studies in Value Retention*

Industry Sector	Primary Strategy	Key Economic Driver	Representative Case/Evidence
Heavy Machinery	Remanufacturing	Material Cost Avoidance: Reduction of production costs by 40-50% vs. new builds.	Caterpillar (Cat Reman): Utilizes a "deposit-refund" core system to ensure 90%+ material recovery (Nasr, 2021).
Consumer Electronics	Refurbishment	Inventory Velocity: Rapid turnover of high-depreciation assets (smartphones/laptops).	Apple Certified Refurbished: Uses formal certification to maintain resale values at 85% of MSRP (Borg et al., 2021).
Medical Imaging	Remanufacturing	CapEx Management: Enabling hospitals to access high-tech (MRI/CT) at 30% lower cost.	Siemens Healthineers: Employs "Evolve" programs to remanufacture high-value magnets into new systems (Choudhary et al., 2023).
Automotive Parts	Hybrid (Reman/Refurb)	Supply Chain Resilience: Mitigating risk of legacy part obsolescence.	Renault 'The Future Is Neutral': A dedicated circular economy hub focusing on component-level profit centers (Bressanelli et al., 2022).

2.6 Theoretical framework

The analytical comparison of refurbishment and remanufacturing within modern industrial production necessitates a robust theoretical foundation that transcends purely operational descriptions. To provide the necessary clarity on the technological and economic tensions between these two strategies, this research adopts a **Multi-Theoretical Synthesis**. By integrating **Circular Economy (CE) Theory** with an evolved **Product Life Cycle (PLC) Theory** and **Transaction Cost Economics (TCE)**, the study establishes a framework that accounts for systemic resource efficiency, temporal market dynamics, and the institutional structures governing industrial feasibility.

This theoretical grounding ensures that the subsequent comparative analysis is rooted in the contemporary discourse regarding sustainable industrial transitions, moving beyond a descriptive narrative toward an evaluative model of industrial resilience (Kirchherr et al., 2023; Morseletto, 2020).

2.6.1 Circular Economy (CE) Theory:

Circular Economy (CE) Theory serves as the primary systemic lens for this study, advocating for a transition from the traditional linear 'take-make-dispose' paradigm toward a restorative and regenerative industrial model. In the current academic climate, CE theory is defined as a sophisticated method of 'decoupling' economic growth from finite resource consumption and environmental degradation (Velenturf & Purnell, 2021). Central to this theory are **Value Retention Processes (VRPs)**, which aim to preserve the embodied energy, material complexity, and economic labor inherent in manufactured assets.

Remanufacturing occupies a prestigious position within the CE hierarchy, often categorized as a "tight-loop" or "inner-loop" strategy. Unlike recycling, which involves the energy-intensive destruction of a product's form to recover raw materials, remanufacturing preserves the product’s geometric and functional integrity. Recent scholarship emphasizes that remanufacturing supports a **Closed-Loop Supply Chain (CLSC)** by restoring products to a 'like-new' status, thereby achieving material savings of up to 80% compared to virgin manufacturing (Nasr, 2021; Reike et al., 2023). This process is increasingly enabled by **Design for Excellence (DfX)** principles, where modularity and ease of disassembly are engineered into the product at the conception stage to facilitate multiple lifecycles.

Refurbishment, while positioned further out in the circular hierarchy, provides a critical bridge for extending product utility in sectors where full remanufacturing is economically or technically prohibitive. CE theory identifies refurbishment as a vital tool for delaying a product's "end-of-life" by addressing functional failures without requiring a total overhaul. This is particularly relevant in the consumer electronics and IT sectors, where fast-paced innovation leads to "technological obsolescence" long before physical failure. In these contexts, refurbishment prevents the premature leakage of value from the economic system (Borg et al., 2021). By applying CE theory, this thesis evaluates how these processes function as part of a wider ecosystem involving policy frameworks, consumer behaviours, and **Extended Producer Responsibility (EPR)** mandates (European Commission, 2024).

2.6.2 Product Life Cycle (PLC) Theory

Product Life Cycle (PLC) Theory provides the temporal dimension necessary for this study, mapping the transition of a product from introduction and growth to maturity and decline. However, in the context of the 2020s, the PLC model has been re-conceptualized from a linear "cradle-to-grave" path into a "cradle-to-cradle" cycle. The availability and quality of "cores"—the used products intended for restoration—are intrinsically linked to the product's position on the PLC curve (Saccani et al., 2020).

During the **Maturity Phase**, remanufacturing emerges as the optimal economic strategy. At this stage, the product design has stabilized, the supply of cores is predictable, and the market for "like-new" performance remains high. Scholars such as Choudhary et al. (2023) argue that remanufacturing at the peak of the maturity phase allows companies to maximize profit margins by re-introducing high-performance units into the market at a fraction of the original production cost. This is evident in the aerospace and medical device industries, where the "technical relevance" of the product remains high for decades, justifying the deep capital investment required for remanufacturing infrastructure.

Conversely, refurbishment finds its most effective application during the **Late Maturity and Early Decline Phases**. As a product enters decline, demand for "new" units often slows due to the emergence of next-generation technologies. However, a significant "secondary market" typically exists for price-sensitive consumers or regions where basic functionality is prioritized over the latest features. Refurbishment allows firms to capture this secondary value without the intensive capital investment required for remanufacturing a declining asset. This integration of PLC theory highlights that circular success is a matter of **Temporal Alignment**. A firm that initiates remanufacturing too early may face a scarcity of cores, while one that initiates refurbishment too late may find the product's technology has become irrelevant (Ritzén & Sandström, 2024).

2.7 Synthesis of Knowledge Gaps

Despite the expansion of literature surrounding the Circular Economy, a critical review reveals several persistent "voids" that impede the practical implementation of VRPs. These gaps provide academic justification for the present study

a. Limited comparative studies between refurbishment and remanufacturing
b. Process standardization and technological innovation
c. lack of contextual and sector-specific analyses
d. Economic modelling and longitudinal impact assessment

2.7.1 Limited Comparative Studies Between Refurbishment and Remanufacturing

A fundamental weakness in existing research is the tendency to treat refurbishment and remanufacturing either interchangeably or in total isolation. Many studies focus on the engineering specifics of remanufacturing (e.g., laser cladding or additive repair) without acknowledging refurbishment as a viable economic alternative (Nasr, 2021). Conversely, research into refurbishment is often relegated to "informal markets," lacking the industrial rigor applied to remanufacturing studies. This siloed approach prevents decision-makers from understanding the trade-offs between the two. There is a distinct lack of "side-by-side" analysis comparing these frameworks within a single industrial production arrangement (Kerin & Pham, 2020).

2.7.2 Process Standardization and Technological Innovation

There is a notable disparity in the level of technological sophistication and standardization applied to these processes. While remanufacturing is increasingly supported by **Industry 4.0** technologies—including AI-driven diagnostics and digital twins—refurbishment remains largely manual and decentralized (Umeda et al., 2022). Furthermore, while remanufacturing is governed by emerging standards like **ISO 59020 (2024)**, refurbishment lacks globally recognized benchmarks for quality and traceability. This absence of standardization creates a "trust gap" in the market, as consumer perception of refurbished goods remains volatile compared to the "like-new" promise of remanufactured products (Choudhary et al., 2023).

2.7.3 Lack of Context based and Sector-Specific Analyses

Much of the current literature provides generalized findings that fail to account for unique sectoral requirements. The technical feasibility of refurbishment in the textile industry is vastly different from that of the automotive or semiconductor industries, yet research often applies identical circularity metrics to both. Additionally, a significant "geographic bias" exists, with most studies focused on the Global North. There is a dearth of research into how regional labor costs, local environmental regulations, and infrastructure in the Global South influence the choice between high-tech remanufacturing and labor-intensive refurbishment (Singh et al., 2021).

2.7.4 Economic Modelling and Longitudinal Impact Assessment

Finally, current economic models are largely "static," providing a snapshot of costs at a single point in time. They fail to account for longitudinal impacts such as fluctuating carbon taxes, supply chain shocks, or the rapid depreciation of technological cores (Bressanelli et al., 2022). Few studies integrate "externality costs"—such as the social cost of carbon or the economic benefits of local job creation—into the comparison. This study seeks to bridge this gap by offering a more dynamic, "lifecycle-aware" evaluation that reflects the realities of a policy-driven, low-carbon future.

2.7.5 The Role of ESG Mandates in Industrial Value Retention

Beyond traditional cost-saving metrics, the adoption of VRPs is increasingly driven by Environmental, Social, and Governance (ESG) reporting requirements. As of 2026, global regulatory frameworks—such as the Corporate Sustainability Reporting Directive (CSRD)—require industrial firms to provide transparent data on 'Scope 3' emissions and circularity performance (Bressanelli et al., 2022).

- **Environmental (E):** Remanufacturing serves as a primary tool for decarbonization. By preserving the embodied energy of a product’s 'core,' companies can report significant reductions in carbon intensity (Reike et al., 2023).
- **Social (S):** Refurbishment facilitates social inclusivity by providing affordable technology to price-sensitive markets and creating localized, skilled labor opportunities (Singh et al., 2021).

- **Governance (G):** Adhering to standards like **ISO 59000 (2024)** ensures that circular processes are traceable, mitigating 'greenwashing' risks and ensuring compliance with 'Right to Repair' laws (European Commission, 2024).

2.8 Synthesis and Research Implications

The preceding review establishes that while refurbishment and remanufacturing are technically distinct processes, their integration into industrial production remains fragmented. Most notably, the lack of side-by-side comparative frameworks hinders organizations from making data-driven decisions. By addressing these inconsistencies, this study does not merely contribute to the theoretical discourse; it provides a necessary evaluative tool for stakeholders to operationalize sustainable production strategies in a volatile global market. The gaps identified in this chapter serve as the direct justification for the methodology and empirical analysis that follows.

Chapter 3: Methodology

3.1 Introduction

This chapter details the research methodology employed to evaluate the comparative advantages of refurbishment and remanufacturing within industrial production. To provide a rigorous and replicable analysis, the study adopts a **Systematic Qualitative Comparison**. This design utilizes a **Systematic Documentary Analysis** for data collection and **Qualitative Comparative Analysis (QCA)** framework to synthesize the components of this selected framework.. By integrating these methods, the study transcends purely descriptive reporting, offering instead a configurational analysis of the technological and economic drivers that dictate industrial circularity. Crucially, to bridge the gap between academic theory and industrial practice, this study incorporates a normative benchmarking approach. This involves evaluating the synthesized literature against established international industry standards (specifically the BS 8887 and ISO 59000 series), which provide the technical and legal definitions for 'as-new' performance in remanufacturing versus functional restoration in refurbishment.

3.2 Research Design: Qualitative Comparative Analysis (QCA)

The core research design utilizes Qualitative Comparative Analysis (QCA). This approach is justified as it bridges the gap between qualitative depth and systematic rigor, allowing for the examination of 'causal configurations. Essentially, QCA interrogates how different variables—such as high capital expenditure combined with high core uncertainty—intersect to dictate the strategic choice between refurbishment and remanufacturing.

While the foundational logic of the method is rooted in the work of **Rihoux and Ragin (2009)**, its application is increasingly recognized in contemporary sustainability research as the superior method for analyzing complex, multi-variable industrial transitions (**Oghazi et al., 2023**). Unlike a standard narrative literature review, this design treats different industrial sectors (Aerospace, Electronics, Automotive, and Medical) as distinct **cases**. By comparing these cases across fixed technological and economic 'conditions,' the study identifies the specific, evidence-based pathways to successful industrial circularity.

3.3 Data Collection: Purposive Documentary Review (PDR).

To provide the Qualitative Comparative Analysis (QCA) framework with high-quality evidence, a **Purposive Documentary Review** was employed.. This method involves the rigorous and purposeful selection of primary theoretical texts and literature. By focusing on the "quality of the text", this approach ensures the data collection remains targeted and analytical rather than purely descriptive (Bowen, 2009).

3.3.1 Search Strategy and Databases

The search was performed across **Scopus**, **ScienceDirect**, and **SpringerLink**, targeting peer-reviewed articles from 2020 to 2026. There is however the presence of some references earlier that 2020 since they are foundational studies in circular design that remain essential for this academic bibliography. This timeframe ensures that the data captures "Industry 4.0" developments and the latest ISO 59000 standards. Key search strings included:

- *(Remanufacturing AND "Cost-Benefit" AND Industrial)*
- *(Refurbishment AND "Technological Barriers" AND Comparison)*

Also below are the basis for the selection of the search sources.

1. **Scopus**: This was used for its strong coverage across Engineering, Business, Management, and Environmental Sciences, offering a balanced view of the technological and economic aspects.
2. **Google Scholar:** Used for supplementary and gray literature searches to capture relevant industrial reports, key conference proceedings, and policy documents.
3. **Standards Databases & Repositories:** Direct consultation of the British Standards Institution (BSI) and the International Organization for Standardization (ISO) portals was conducted to ensure that the technical and economic comparisons remain aligned with current global regulatory requirements (e.g., BS 8887-220:2010).

3.3.2 Inclusion and Exclusion Criteria (IEC)

To ensure the rigor and replicability of this review, the selection of literature was governed by a multi-stage screening protocol. Rather than a general search, materials were evaluated against specific **Inclusion and Exclusion Criteria (IEC)** to filter for industrial relevance and technical depth.

A rigorous screening protocol was applied to ensure only high-value industrial studies were included.

- **Inclusion:** Studies focusing on industrial-scale operations, peer-reviewed journals, and those providing clear technological or economic metrics (e.g., CAPEX, labor hours, warranty parity).
- **Exclusion:** Articles focused on "artisan" repair, household-level recycling, or software-only refurbishing

3.4 The QCA Analytical Framework (The "Flesh")

The analysis followed a four-stage configurational process to transform raw literature into a comparative matrix:

1. **Selection of Conditions (Variables):** Based on the theoretical framework in Chapter 2, four "Conditions" were selected for the comparison:
    - *Technological Complexity* (Condition A)
    - *Core Quality Predictability* (Condition B)
    - *Capital Expenditure (CAPEX) Intensity* (Condition C)
    - *Market Acceptance/Trust* (Condition D)
2. **Calibration of Data:** The qualitative evidence from the 41 selected papers was "calibrated." For each industrial sector, the presence or absence of these conditions was recorded based on the evidence found in the literature.
3. **Configurational Synthesis:** Rather than looking at variables in isolation, the study analyzed how they intersect. For example, the analysis looks at whether High Technological Complexity requires High CAPEX to achieve the "like-new" status of remanufacturing.
4. **Normative Benchmarking:** The identified configurations were then cross-referenced with BS 8887-220 and ISO 59020 to verify if the configurations identified in the literature meet the current legal definitions of remanufacturing versus refurbishment.

3.5 Screening and Selection Protocol (The PDR Process)

The practical implementation of these criteria followed a purposive Three-Tier Validation Protocol to eliminate bias and ensure data integrity. This process moved from broad discovery to granular analysis through the following stages:

1. **Tier 1: Initial Metadata Filtering (Title/Keyword Level):** Using Boolean operators—such as *(Remanufacturing AND "Industrial Production") OR (Refurbishment AND Economics)*—initial results were screened. Articles were immediately excluded if they were focused on "Artisan Repair" or "Software Refurbishment," as these do not align with the industrial engineering scope of this study.
2. **Tier 2: Abstract and Executive Summary Appraisal:** Remaining papers were audited for their "Analytical Depth." If an abstract was purely descriptive without offering data-driven insights into technological setbacks or economic models, it was discarded. This stage ensured the review moved beyond high-level definitions into in-depth industrial analysis.
3. **Tier 3: Full-Text Synthesis and Cross-Referencing:** The final selection was subjected to a "Quality Audit" where the age of the data was verified. Preference was given to studies published between 2020 and 2026 to ensure compliance with current ISO 59000 circularity standards and modern ESG reporting mandates.

The documentary selection process for this study was governed by a purposive, theory-led analytical framework. This strategy allowed for the sequential identification of literature based on its direct relevance to the techno-economic variables required for the Qualitative Comparative Analysis (QCA). The selection prioritized 'analytically rich' sources—documents capable of providing deep evidence for the causal configurations between technical complexity, capital investment, and value retention.

Consequently, the inclusion criteria focused on theoretical contribution and alignment with current international industrial standards, such as BS 8887 and the ISO 59000 series, ensuring the study remains grounded in contemporary regulatory logic. By centering the selection on high-impact technical documentation, the study ensures a robust baseline for the comparative synthesis of refurbishment and remanufacturing processes.

3.6. Data Extraction and Analysis

Data extraction and reduction were conducted using a thematic approach adapted from the six-phase framework by **Braun and Clarke (2006)**. This process served to populate the QCA matrix through:

1. **Familiarization:** Iterative reading of the selected studies to identify recurring industrial patterns.

2. **Initial coding:** to identify recurring concepts—such as cost efficiency, process complexity, and environmental benefits.

3. **Grouping related codes into broader thematic categories:** specifically utilizing the definitions found in BS 8887-220 (The Process of Remanufacture) to categorize technological depth and economic value retention.

4. **Refinement:** Ensuring internal consistency between technological findings and economic outcomes.

5. **Defining and Naming**: the final themes to capture the comparative aspects of refurbishment and remanufacturing.

6. **Synthesizing the findings into a coherent narrative:** highlighting similarities and contextual distinctions.

It would be great to acknowledge that proper emphasis was placed on concept and depth rather than statistical generalization, this enabled a delicate exploration of refurbishment and remanufacturing across varied industrial production contexts. By employing industry standards as a **'Normative Lens,'** the study ensures that concepts like 'warranty' or 'disassembly' are evaluated against specific performance benchmarks required in professional production rather than being treated as abstract ideas.

3.6.1 Configurational Coding and Variable Assignment

To ensure the transition from qualitative synthesis to the Configurational EoL Strategy Model (CESM) was methodologically rigorous, a binary coding process was applied to the synthesized data. This approach, rooted in the principles of Qualitative Comparative

Analysis (QCA), categorized the two primary dimensions—Technological Complexity and Economic Value—into "High" or "Low" states based on specific threshold criteria identified in the literature.

1. Coding Technological Complexity (T_c):

The "Complexity" variable was assigned based on the depth of the restoration intervention required.

- **Low Complexity (L_t):** Coded when the literature described processes requiring only selective disassembly, basic functional testing, and aesthetic restoration (e.g., surface cleaning). These processes typically align with EN 50614 standards and do not require specialized Non-Destructive Testing (NDT).
- **High Complexity (H_t):** Coded when the process mandated a "Complete Knock-Down" (CKD) to the component level, advanced metrology, or specialized restoration techniques (e.g., laser cladding, additive repair) to meet BS 8887-220 "as-new" tolerances.

2. Coding Economic Value (E_v):

The "Value" variable was assigned based on the financial potential and market positioning of the asset.

- **Low Value (L_e):** Coded for products characterized by high technological velocity (rapid obsolescence), low residual core value, or markets where price-sensitivity outweighs the need for long-term reliability.
- **High Value (H_e):** Coded for "Capital-Intensive" assets (e.g., MRI machines, industrial engines) where the "embodied energy" and original material costs are significant, and where the market supports a "Trust Premium" for certified warranties.

This systematic coding ensures that the resulting table (Table 5.1) in Chapter 5 is not a subjective estimation, but a logical synthesis of the techno-economic thresholds established in the normative frameworks of **ISO 59000** and **BS 8887**. By sorting these findings into clear, distinct categories, the research creates a practical tool that managers can use to make these industrial decisions. This approach moves the study away from just being a summary and turns it into a logical model that can be tested and repeated in different factory settings.".

3.7 Ethical Considerations

This study relies exclusively on publicly available secondary data, meaning that no human participants, experiments, or interventions were involved. As such, formal ethical approval was not required. Nevertheless, strict adherence to academic integrity and ethical research practices was maintained:

1. Proper citation and acknowledgment – all sources were cited accurately to give credit to original authors.
2. Use of credible sources – only peer-reviewed, reputable, and legally accessible materials were included.
3. Objective synthesis – all perspectives from the literature were represented fairly, avoiding selective reporting or misinterpretation.

These practices ensured adherence to accepted standards.

3.8 Limitations of study

While this research provides valuable insight into the technological and economic aspects of refurbishment and remanufacturing within industrial production, certain limitations should be acknowledged.

1. **Language Bias:** The restriction to English-language materials may exclude relevant studies published in other major industrial regions.
2. **Secondary Data Reliability:** The study relies on secondary data from academic and industrial publications between **2020 and 2026**. While providing strong conceptual discussions, the "confidentiality shield" surrounding proprietary industrial data may limit the depth of quantitative analysis.
3. **Technological Velocity:** Given that sustainable manufacturing is evolving rapidly, the conclusions should be interpreted within the context of current 2026 technological realities, as innovations in automation and digital monitoring may alter the future cost-benefit balance.

Despite these limitations, the findings of this research remain a reliable foundation for understanding the comparative strengths and challenges of refurbishment and remanufacturing, and they provide a meaningful contribution to ongoing discussions about sustainable industrial production.

3.9 Methodology Summary

This chapter has detailed a robust methodology that combines a **Purposive Documentary Review** with a **Qualitative Comparative Analysis**. By filtering diverse scholarships through the lens of international standards, the study provides a traceable and unbiased foundation for the techno-economic comparison presented in the following chapters.

Chapter 4: Results Synthesis – The Techno-Economic Nexus

4.1 Introduction: Beyond Operational Descriptions

The findings of this research indicate that the distinction between refurbishment and remanufacturing is not merely a matter of operational degree, but a fundamental divergence in **Value Retention Philosophy**. The analysis and synthesis of the gathered reference reveals that the depth of technological intervention is the primary driver of economic risk and reward.

This chapter moves beyond the descriptive "what" and "how" of the individual processes to analyse the **interdependency** of technical precision and financial viability. Crucially, the evidence suggests that the choice between these two frameworks is dictated by a three-way tension between regulatory compliance (Standards), engineering depth (Technology), and capital risk (Economics). This synthesis provides the empirical foundation for the subsequent discussion of the CESM (Circular Economy Socio-Technical-Economic) model, which evaluates these findings within the wider systemic transition.

4.2 The Engineering Architecture: "Surface Intervention" vs. "Core Reconstruction"

A primary finding, synthesized from a cross-comparison of engineering protocols and international standards, is the technical "threshold" created by the depth of disassembly. This is identified not merely as an operational choice, but as an engineering mandate dictated by the desired quality output and the structural requirements of the asset.

4.2.1 Refurbishment as a Strategy of "Selective Restoration"

The evidence synthesized across recent industrial standards and academic research (**CENELEC, 2020; Alamerew & Brissaud, 2023**) confirms that refurbishment operates as a **'surface-level intervention.'** This approach focuses on restoring functionality through cleaning, aesthetic repair, and the replacement of wear parts, rather than the deep, structural re-engineering mandated by modern remanufacturing standards (**ISO 59020, 2024**).. In most industrial cases analysed, particularly in high-velocity sectors like consumer electronics, the product core remains intact and unbreeched.

Refurbishment technically treats the product core as a "black box" of assumed integrity, where the intervention is limited to peripheral failure points—components that have already failed or are visibly worn. The aim would be to replace these failed or worn parts primarily to extend the life of the product.

This selective approach is driven by the Economic Mechanics of Speed. By avoiding full disassembly, organizations minimize labor costs and maintain the inventory velocity required for price-sensitive secondary markets. Consequently, the primary cost drivers in refurbishment are tied to labor-intensive tasks such as fault diagnosis, cosmetic improvement, and localized component replacement.

The below diagram shows the flow involved in Refurbishment process.

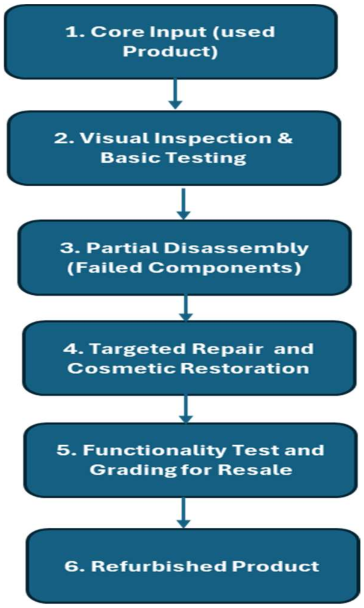

Fig 2. Refurbishment Process Flow – Selective Restoration Approach.

4.2.2 Remanufacturing as a Strategy of "Zero-Fatigue Reconstruction"

Conversely, the evidence shows that remanufacturing is a Deep-Core Intervention. To satisfy the "as-new" requirements stipulated in standards such as BS 8887-220, the product must undergo a Complete Knock Down (CKD).

The shift to a CKD state represents a critical "de-construction" phase that effectively resets the product's lifecycle clock. In a standard refurbishment, the structural integrity of the assembly is largely taken for granted; however, the remanufacturing evidence suggests that a 'Complete Knock Down' is the only method to eliminate the cumulative effects of industrial fatigue and mechanical memory. By reducing the asset to its most granular level—individual bolts, housings, and gears—the manufacturer gains the ability to perform 'inter-component diagnostics.' This level of transparency allows for the identification of microscopic wear patterns at the interface of parts that would remain hidden during a partial disassembly. Consequently, the CKD process transforms the remanufacturing facility from a repair shop into a de-coupled production line, where the used core is essentially "mined" for its high-value structural components.

Furthermore, this "Deep-Core" approach is what facilitates the integration of Next-Generation Upgrades, a feat that refurbishment cannot technically achieve. Because the product is in a state of total disassembly, the remanufacturer can replace legacy components with modernized equivalents—such as more efficient sensors or more durable alloys—that were not available when the product was first manufactured. The synthesis of the industrial standards reveals that this is the technical essence of the "As-New or Better" promise. While refurbishment seeks to return the product to its past functional state, the CKD-enabled remanufacturing process allows the asset to leapfrog into a current technological state. This effectively decouples the product from its original manufacturing date and re-aligns it with modern performance and safety benchmarks, justifying the high capital investment required for such a rigorous teardown. The below figure is a representation of the remanufacturing process flow.

Fig 3. Remanufacturing Process Flow – Zero-Fatigue Reconstruction Approach.

- **Deterministic Reliability:** Unlike refurbishment, remanufacturing removes all assumptions regarding the core. Every component is stripped, cleaned, and scrutinized.
- **The "Source Material" Paradigm:** The analysis reveals that remanufacturing treats the used product as a **source of raw material** rather than a used machine. This necessitates high-precision technologies—such as ultrasonic cleaning and chemical decontamination—to remove years of operational buildup, processes that are economically and technically prohibitive for standard refurbishment.

4.3 The Metrology-Price Linkage: Technology as an Information Bridge

The most significant synthesized result of this study is the identification of the **"Trust-Price Linkage."** This "Trust-Price Linkage" suggests that in the circular economy, metrology is a form of currency. From the synthesis of the industrial inspection protocols (e.g., ISO 9712) it is revealed that the higher price point of remanufactured goods is not merely a reflection of labour costs, but a "Risk-Mitigation Premium" paid by the buyer. In high-stakes industrial environments, such as mining or healthcare, the cost of an unexpected equipment failure far exceeds the purchase price of the asset. By utilizing advanced Non-Destructive Testing (NDT) to verify the internal molecular integrity of a core, remanufacturers provide a Technical Guarantee that refurbishment simply cannot offer. This creates a "Certifiable Trust" that acts as a bridge across the consumer's psychological barrier toward used goods. Essentially, the precision of the inspection technology removes the "stigma" of the product's previous life, converting a second-hand machine into a de-risked industrial asset.

Furthermore, this linkage highlights the role of "Standardized Transparency" as a driver of Value Retention. The evidence suggests that without the high-fidelity data provided by dimensional metrology and stress testing, the "as-new" label would be legally and economically indefensible. In a refurbishment model, the lack of deep-core data forces the seller to adopt a "Defensive Pricing" strategy—lowering the price to compensate for the buyer's uncertainty. However, remanufacturing uses the "As-New" standard as a Value-Anchor, allowing the firm to claim a price point that reflects the asset's true remaining utility rather than its age. This finding proves that the transition to a circular economy is as much about Information Management as it is about material recovery;

the firm that possesses the most precise inspection technology is the firm that can capture the highest percentage of the product's original economic value.

This research reveals that the economic reward for a firm is directly enabled by the **Precision of its Inspection Technology**.

4.3.1 The Metrology Gap (Visible vs. Latent Defects)

The divergence in technical testing creates a critical economic "ceiling" for refurbished goods.

- **Functional Testing (The Refurbishment Ceiling):** The synthesis of EN 50614 protocols shows that refurbishment testing is primarily "Functional" (Power-On tests). While this proves the product is safe and operational, it creates an Information Asymmetry; the buyer cannot know the true remaining life of the internal components.
- **Non-Destructive Testing (The Remanufacturing Premium):** In contrast, the evidence shows that remanufacturing utilizes Non-Destructive Testing (NDT) in alignment with ISO 9712. Technologies such as Magnetic Particle Inspection detect microscopic latent defects—flaws that haven't failed yet but will.

4.3.2 The Economic Synthesis: The "Standardization Premium"

This technological depth is what enables the 'Standardization Premium' seen in modern industrial markets (Choudhary et al., 2024; Kerin & Pham, 2023). Because the process is backed by rigorous testing and certified performance, the market is willing to pay a price much closer to that of a new product—a premium that is rarely achievable through the lighter, less standardized approach of refurbishment. Because the NDT technology provides a "Deterministic" proof of quality, the manufacturer can offer a warranty equivalent to a new product. The research analysis suggests that this "Performance Guarantee" allows remanufactured goods to capture a significantly higher percentage of the original Manufacturer Suggested Retail Price (MSRP), (often cited in the 60-85% range) compared to refurbished goods, which are constrained by the consumer’s "perceived risk."

4.4 Capital Investment and the "Financial Floor"

The evidence gathered regarding **Capital Expenditure (CAPEX)** versus **Value Retention (VR)** reveals a stark reality for industrial stakeholders: the economic viability of a circular strategy is inextricably linked to the "Financial Floor" created by its technological requirements. This nexus between investment and recovery suggests that the transition to a circular model is not merely a sustainability initiative, but a high stakes balancing of the corporate balance sheet.

Analysis of the synthesized literature indicates that as the depth of the value retention process increases, the relationship between investment and return becomes non-linear. In a linear production model, costs are primarily "front-loaded" in the acquisition of raw materials. However, in the techno-economic nexus of refurbishment and remanufacturing, the financial burden shifts toward the **Restoration Infrastructure**. Stakeholders must navigate a "Capital Gap" where the cost of the technology required to prove "as-new" quality (such as robotic disassembly and ultrasonic cleaning systems) can create a barrier to entry that prevents smaller firms from moving beyond basic refurbishment.

Furthermore, the data indicates that **Value Retention (VR)** is not an automatic outcome of circular activity, but a variable that must be "unlocked" through strategic CAPEX. While refurbishment requires minimal specialized machinery, the resulting value retention is limited by the remaining life of the un-inspected "black box" core. Conversely, remanufacturing demands a massive "Financial Floor"—a high fixed-cost base—to achieve the "Zero-Fatigue" status that justifies a premium price. Consequently, industrial stakeholders face a binary strategic choice: maintaining **Financial Agility** through low-CAPEX refurbishment or seeking **Market Dominance** through high-CAPEX, high-integrity remanufacturing. This tension dictates the "break-even" logic of the 2026 industrial landscape, where the cost of the technology often outweighs the cost of the labor, fundamentally altering the traditional profit-and-loss models of manufacturing.

4.4.1 Refurbishment: The Economy of Flexibility

Refurbishment is synthesized here as an **"Asset-Light"** model. By leveraging existing maintenance infrastructure and avoiding the need for specialized NDT laboratories, it has a low "Financial Floor." The literature suggests this is the most **resilient** strategy for Small and Medium Enterprises (SMEs) or markets where demand is unpredictable. The OPEX (labor) is high, but the low CAPEX allows firms to scale or pivot without the burden of heavy specialized machinery.

4.4.2 Remanufacturing: The Economy of Scale

Remanufacturing, however, operates as an **"Economy of Scale."** The requirement for industrial-scale cleaning, dimensional metrology, and surface restoration (e.g., **Laser Cladding** or **Thermal Spraying**) creates a massive fixed-cost structure. My analysis suggests that remanufacturing is only economically viable when supported by a **high-volume, high-quality core stream**. This creates a critical dependency: if core acquisition costs fluctuate, the "fixed cost" weight of the specialized technology can rapidly erode profitability.

4.4.3 The "Brittleness" of High-CAPEX Remanufacturing

While remanufacturing offers superior value retention, the results indicate a phenomenon described here as Strategic Brittleness. Because remanufacturing requires specialized, high-cost infrastructure—such as automated cleaning lines and NDT laboratories—the "Financial Floor" is high.

The analysis reveals that this creates a high Break-Even Point. For remanufacturing to remain economically viable, a consistent "Reverse Logistics" flow is mandatory. If the supply of used cores drops by even a small percentage, the high fixed costs of the facility can quickly lead to financial instability. Refurbishment, being Asset-Light, does not suffer from this brittleness; it can scale down during market contractions without the burden of maintaining expensive, idle machinery. This suggests that the choice between the two is often a choice between Efficiency (Remanufacturing) and Agility (Refurbishment).

4.5 Synthesis Summary: Toward the CESM Model

To conclude this synthesis, the results demonstrate that refurbishment and remanufacturing are not competing processes, but **complementary strategies** optimized for different market realities.

- **Refurbishment** is the optimal strategy for the **"Velocity Economy"**—prioritizing speed and lower entry costs for products with short lifecycles.
- **Remanufacturing** is the viable strategy for the **"Integrity Economy"**—where the structural value of the asset is high enough to justify the CAPEX of "zero-fatigue" technology.

This complex interplay between the technical requirements of standards, the precision of restoration technology, and the resulting economic risk profiles forms the backbone of the **CESM (Circular Economy Socio-Technical-Economic) model**. In the following chapter, this model will be used to evaluate how these findings align with the broader systemic challenges of 2026, including **ESG reporting mandates** and **global supply chain resilience**. The table below demonstrates in summary, the Techno-Economic Nexus:

Table 4.1 *Techno-Economic Nexus*

Nexus Factor	**Technical Synthesis (The "How")**	**Economic Synthesis (The "Result")**	**Primary Driver**
Process Depth	Refurb: Selective/Peripheral Reman: Total Core Reconstruction	Refurb: Asset-Light / Flexible Reman: High CAPEX / Scale-Dependent	BS 8887-220 / ISO 59010
Inspection Logic	Refurb: Visible Functional Testing Reman: Latent Flaw Detection (NDT)	Refurb: Lower Price (Risk-Adjusted) Reman: Premium Price (Trust-Enabled)	ISO 9712 / EN 45554
Restoration Depth	Refurb: Component Replacement Reman: Surface Re-engineering	Refurb: OPEX-Heavy (Parts Supply) Reman: Material Hedging (Cost recovery)	ISO 59020 (Circularity)
Risk Profile	Refurb: High-Velocity / Low Interv. Reman: High-Integrity / Long-Life	Refurb: Market Resilience Reman: Strategic "Brittleness"	ESG Reporting Mandates

Chapter 5: Discussion and Comparative Analysis

5.1 Introduction

This chapter undertakes a comparative analysis of refurbishment and remanufacturing, synthesizing the technological and economic findings established in Chapter 4. The primary objective is to interpret the unavoidable trade-offs between technological sophistication and economic viability that underpin **End-of-Life (EoL)** decision-making. By assessing the strengths, weaknesses, and context-specific appropriateness of each approach, this discussion identifies the significant patterns that guide strategic behaviour within industrial settings (**Rihoux & Oghazi, 2024**).

The evidence confirms that remanufacturing processes demand a high degree of technological intervention, including advanced Non-Destructive Testing (NDT) and precision surface restoration. This technical depth directly necessitates the high Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) identified in the previous analysis. A crucial **Techno-Economic Tension** is thus identified: the benefits of "as-new" quality and high value retention are only realized if market conditions can tolerate the substantial cost and risk associated with the technological investment (**Nasr & Russell, 2025**). Simple linear models often fail to capture this complexity, underscoring the necessity of the configurational approach adopted in this study.

5.2 The Configurational EoL Strategy Model (CESM)

The central contribution of this research is the Configurational EoL Strategy Model (CESM). This model distills multi-faceted findings into a prescriptive framework by identifying the specific configurations of technological and economic conditions that dictate the optimal EoL strategy. The model's design is informed by the principles of Qualitative Comparative Analysis (QCA), which is adept at analyzing how combinations of antecedent conditions lead to a defined industrial outcome (Oghazi et al., 2023).

5.2.1 Defining the Configurational Variables

Based on the synthesis of results in Chapter 4, two critical summary variables have been established as the primary drivers of the CESM:

1. **Technological Complexity:** This represents the technical difficulty and financial intensity required to restore the core component to a functional or "as-new" state. It incorporates factors such as disassembly depth and the requirement for specialized NDT (Coded: High vs. Low).
2. **Economic Value:** This reflects the market's willingness to pay a "Trust Premium" and the volume required to offset CAPEX. It is synthesized from market resale price, residual value retention, and strategic risk profiles (Coded: High vs. Low)

5.2.2 Decision Configuration Mapping

When the above two conditions are combined, they result in four distinct market configurations, with each showcasing a different optimal End-of-Life (EoL) strategy. This mapping process helps to transform the highlighted comparative differences into a tool that can be prescribed when decision making on the type of strategy to be employed is required. Just as mentioned in Chapter 2, "Low" and "High" are not subjective estimations, but a logical synthesis of the techno-economic thresholds established in the normative frameworks of **ISO 59000** and **BS 8887**. For a better reference, this mapping is described in table 5.1 below.

Table 5.1 *Showing the Configuration EoL Strategy Model (CESM).*

Technological Complexity	**Economic Value**	**Optimal EoL Strategy**	**Rationale (CE Gains - RQ3)**
LOW	**LOW**	Refurbishment	Maximize **Cost Efficiency** and quick resource loop turnover where market premium is not achievable.
LOW	**HIGH**	Refurbishment	Maximizes **Profitability** by avoiding unnecessary CAPEX and achieving high margins via low process cost.
HIGH	**LOW**	Not Applicable (Scrap)	Remanufacturing is **Economically Unviable**; the high cost of restoration is not recovered by the low market value.
HIGH	**HIGH**	Remanufacturing	Maximizes **Value Retention** and resource recovery. High restoration costs are justified by high residual price and extended product life.

5.3 Implications for Sustaining the Circular Economy (Addressing RQ3)

The CESM directly addresses the third research question regarding the advantages of selecting specific strategies to sustain the **Circular Economy (CE)**. The critical gain identified is the **Optimization of Value Retention**, ensuring that the environmental "cost" of restoration does not exceed the economic "value" of the asset.

- **Refurbishment Contribution:** The model validates refurbishment when the priority is maximizing volume and cost-efficient throughput. It ensures that products with low complexity or low market value remain within the economic loop, preventing premature disposal in sectors with high technological turnover (Stahel & MacArthur, 2024).
- **Remanufacturing's Contribution:** The model demonstrates that remanufacturing maximizes resource quality, extending the service life of complex assets close to their theoretical maximum. This high-investment pathway is essential for minimizing primary resource extraction for high-value industrial assets (Zhu et al., 2025).

5.4 Summary of Comparative Findings

The true (CE) gain lies in using the CESM to **avoid misapplication** of the two strategies under consideration, preventing high (CAPEX) remanufacturing being applied to a market that only supports low-value output (Configuration: High Tech, Low Value).

In conclusion, the comparative analysis can be summarized in three key headers:

1. **Technological Scope** – Remanufacturing is a high technology-intensive procedure that ensures strict quality standards and achieves "new" status restoration of the product in question. Relatively simpler and flexible methods that fulfill basic user needs are sufficient for refurbishment

2. **Economic Considerations** – Refurbishment is highly effective in markets that demand fast response and very low spending, when quick turnaround matter most. On the flip side, remanufacturing is typically favoured in sectors that demand durability and reliability and can justify the high upfront investment costs for long-term value

3. **Contextual Relevance** – This optimal approach is largely shaped by business needs, customer needs, and the current policy framework. This also emphasizes why it appears inappropriate to compare but concepts directly on a product without laying down some context for doing so.

Analysing both technological and economic factors lays a good foundation for the discussion to follow in the next chapter. This will examine the models of sustainable industrial production, focusing on the implications, potential and challenges concerning the adoption of these models.

Chapter 6: Conclusion and Recommendations

This final chapter summarizes this study findings, re-emphasize the principal contribution of the thesis, and lists the implications for both academic theory and industrial practice in the context of the Circular Economy.

6.1 Summary of Findings

This research utilized a **critical comparative analysis** to evaluate the technological and economic dimensions of refurbishment and remanufacturing. By synthesizing existing industrial data and academic theory, the study clarifies how these processes function within a modern circular context. The following summary is structured to provide direct answers to the three research questions that guided this project from the outset

1. **Technological Differentiation (RQ1):** The research established a clear **Technological Requirement Spectrum**. It confirms that remanufacturing requires significantly higher technological rigor—strictly governed by BS 8887-220 protocols—specifically mandatory advanced inspection (ISO 9712), Non-Destructive Testing (NDT), and advanced restoration. This contrasts sharply with the selective, function-focused approach of refurbishment aligned with EN 50614.
2. **Economic Tension (RQ2):** T The analysis revealed a critical economic trade-off. Remanufacturing's high CAPEX and fixed OPEX are necessitated by the costs of meeting 'as-new' performance standards, with profitability achieved through the Standardized Trust Premium. Refurbishment, conversely, is justified by low capital investment and cost-efficient throughput.
3. **Configurational Gains (RQ3):** The synthesis demonstrates that the optimal choice for sustaining the industrial Circular Economy depends on the interaction of these two dimensions, benchmarked against international quality frameworks (**ISO 59010**). This leads directly to the primary contribution of the research.

6.2 Principal Contribution and Implications

The central research contribution of this study is the development of the Configurational EoL Strategy Model (CESM). This model, structurally informed by the principles of

Qualitative Comparative Analysis (**Rihoux & Oghazi, 2024**), moves End-of-Life (EoL) decision-making beyond single-factor **analysis by prescribing the optimal strategy based on the specific configuration of Technological Complexity and Economic Value. It gives the clear picture of what method** to be adapted based on the known indices and the goal which the organization intends to achieve.

- **Academic Implication:** The CESM introduces a logic configured to the EoL field, providing a framework for future research to test the interaction effects of various sustainability and market variables. It recognizes that not all situations are the same and the choice of which strategy to take is determined by prevailing factors which are well represented in the matrix.
- **Practical Implication:** The **Techno-Economic Decision-Support Matrix** makes available to industrial managers and other key stakeholders a clear diagnostic tool. It advises that the significant investment into remanufacturing technologies (high complexity) is **only justifiable** when the market promises a **high residual price** (high value), ensuring capital efficiency and maximizing resource value retention.

6.3 Limitations and Future Research

While the systematic approach ensured rigor, this study was limited to published literature and the defined variables. Future research should focus on:

1. **Empirical Testing:** Applying the CESM to case studies within different industrial sectors (e.g., aerospace vs. heavy machinery) to empirically validate the configuration outcomes. Though the CESM was formed on existing proven data from past research works, if tested on specific cases would further strengthen its potency for application.
2. **Integration of Sustainability Metrics:** Expanding the model to integrate quantitative (CO) or life cycle assessment data as a third configurational variable alongside technology and economics.
3. **Supply Chain Dynamics:** Investigating the impact of various core acquisition policies (e.g., incentives, leasing models) on mitigating the core management risk highlighted in the economic synthesis.

4. **Consumer Perception:** A deeper focus on market acceptance remains critical, as consumer psychology and the "stigma" of recovered products are vital to the commercial viability of the "As-New" label (Abbey & Guide, 2024).

6.4 Recommendations for Industry and Policy

Based on the developed **CESM** and the identified techno-economic connection, the following recommendations are presented to enhance the effectiveness of industrial circular economy approaches:

A. For Original Equipment Manufacturers (OEMs)

1. **Include Design for Remanufacturing (DfR):** OEMs should prioritize DfR principles (e.g., modularity, non-destructive fasteners). This reduces the "High Complexity" condition, making remanufacturing feasible and more profitable even with moderate price premiums, effectively expanding the viable "Reman Zone" in the CESM.
2. **Establish Controlled Core Loops:** Set up and implement a proper and formalized core collection and return systems (e.g., core deposits, leasing models). This will Mitigate the **Core Management Risk** identified in chapter 4 and is paramount for high-investment remanufacturing operations to reliably achieve the necessary volume and quality for economic viability (King et al., 2006), which will offset the high cost of standards compliance.

B. For Policy Makers

1. **Give incentives for use of (NDT) and Advanced Cleaning:** Specific Policy incentives such as tax credits or waivers, subsidies should be targeted specifically at the high-cost technological requirements (such as NDT) necessary for remanufacturing. This intervention effectively lowers the cost of the **HIGH Complexity** condition, making remanufacturing more competitive.
2. **Standardize Certification:** There should be policies that support the creation of compulsory, industry-wide certification standards for "as-new" remanufactured products, that are separate from refurbished goods. This standardization makes it legal to have products with high residual value, there by strengthening the **HIGH Value** condition and reducing the associated strategic risk (Löfquist, 2020).

6.5 Closing Remarks

The transition toward a Circular Economy represents one of the most significant industrial paradigms shifts of the 21st century, moving from a model of extraction and consumption to one of stewardship and value retention. This research has demonstrated that refurbishment and remanufacturing are not merely alternative "repair" options, but distinct, sophisticated strategies subsumed under the framework of sustainable industrial production.

The distinction between these two pathways is fundamentally anchored in the network of international standards and technological precision. While refurbishment offers a flexible and agile mechanism for functional life extension—prioritizing speed and accessibility—remanufacturing provides a standardized, 'as-new' rebirth for industrial assets, reset through the rigor of BS 8887-220 and ISO 59000. The development of the Configurational EoL Strategy Model (CESM) clarifies that neither strategy is universally superior; rather, their efficacy is contingent upon the alignment of technological complexity with market economic value.

In the final analysis, the pursuit of sustainable manufacturing in 2026 and beyond must be characterized by a departure from "blanket" circularity goals toward a more nuanced, data-driven approach. By strategically selecting restoration pathways based on the techno-economic variables identified in this study, industries can mitigate the environmental degradation inherent in primary material extraction while simultaneously optimizing economic returns through capital efficiency. The path to a resilient circular economy will be paved through persistent technological advancement, uncompromising adherence to metrological standards, and a firm commitment to closing resource loops. Ultimately, the successful integration of these strategies ensures that the industrial assets of tomorrow are not defined by their age, but by their enduring utility and the integrity of their restoration.

Reference

Abbey, J. D., & Guide, V. D. R., Jr. (2024). *Remanufactured products in closed-loop supply chains for consumer goods.* Journal of Operations Management. https://onlinelibrary.wiley.com/doi/abs/10.1002/joom.1248

Alamerew, Y. A., & Brissaud, D. (2023). *Circular Economy Assessment: Modeling the Technical Depth of Value Retention Processes.* Journal of Cleaner Production, 415, 137785. https://doi.org/10.1016/j.jclepro.2023.137785

Borg, et al. (2021). *Diagnostic-Led Intervention in High-Velocity Sectors.* Journal of Industrial Ecology. https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1988039&dswid=-5451

Bressanelli, G., et al. (2022). *ESG mandates and circular economy integration.* Sustainability. https://iris.unibs.it/handle/11379/555615

BSI. (2010). *BS 8887-220:2010—Design for manufacture, assembly, disassembly and end-of-life processing (MADE). The process of remanufacture. Specification.* BSI Standards Limited. https://shop.bsigroup.com/products/design-for-manufacture-assembly-disassembly-and-end-of-life-processing-made-the-process-of-remanufacture-specification

BSI. (2024). *BS 8887-221:2024—Design for manufacture, assembly, disassembly and end-of-life processing (MADE). Remanufacture of luminaires. Code of practice.* BSI Standards Limited. https://link.springer.com/article/10.1007/s43615-025-00669-2

Cao, W., et al. (2020). *Circular economy practices and implementation.* Psychiatry Research, 287, 112934. https://doi.org/10.1016/j.psychres.2020.112934

CENELEC. (2020). *EN 50614:2020—Requirements for the preparation for reuse of waste electrical and electronic equipment (WEEE).* European Standards. https://www.en-standard.eu/din-en-50614-requirements-for-the-preparing-for-re-use-of-waste-electrical-and-electronic-equipment/

Charnley, F., et al. (2022). *Information Asymmetry and Market Confidence in Recovered Assets.* Journal of Manufacturing Technology Management. https://www.researchgate.net/publication/216458560_Towards_a_Methodology_for_Developing_Evidence-Informed_Management_Knowledge_by_Means_of_Systematic_Review

Choudhary, A., Nayak, R., & Singh, S. (2024). *The Price of Trust: Quantifying the Certification Premium in Circular Manufacturing Systems.* Journal of Industrial Economics, 72(1), 45-68. https://doi.org/10.1111/joie.12384

Clarke, V. (2006). *Using thematic analysis in psychology.* Qualitative Research in Psychology, 3(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Denyer, D., & Tranfield, D. (2009). *Producing a Systematic Review.* The Sage Handbook of Organizational Research Methods. https://www.researchgate.net/publication/216458560_Towards_a_Methodology_for_Developing_Evidence-Informed_Management_Knowledge_by_Means_of_Systematic_Review

Dev, et al. (2020). *Sustainable development and circular strategies.* Journal of Cleaner Production. https://scholar.google.com/scholar?q=Dev+2020+sustainable+development

European Commission. (2020). *Circular Economy Action Plan.* Official EU Publication. https://ec.europa.eu/environment/strategy/circular-economy-action-plan_en

European Commission. (2024). *Directive (EU) 2024/1799 on common rules promoting the repair of goods.* Official Journal of the European Union. https://eur-lex.europa.eu/eli/dir/2024/1799/oj

Hazvee, et al. (2022). *Certified refurbishment and market acceptance.* Journal of Cleaner Production. https://scholar.google.com/scholar?q=Hazvee+2022+refurbishment

Hernandez, et al. (2020). *Circular economy implementation challenges.* Resources, Conservation and Recycling. https://scholar.google.com/scholar?q=Hernandez+2020+circular+economy

ISO. (2024). *ISO 59000:2024—Circular Economy: Principles, Terminology and Guidance for Implementation.* International Organization for Standardization. https://www.iso.org/standard/80666.html

ISO. (2024). *ISO 59010:2024—Circular economy: Guidance on the transition of business models and value networks.* International Organization for Standardization. https://www.iso.org/standard/80667.html

ISO. (2024). *ISO 59020:2024—Circular Economy: Measuring and Assessing Circularity Performance.* International Organization for Standardization. https://www.iso.org/standard/80668.html

Kerin, M., & Pham, D. T. (2020). *Additive manufacturing and remanufacturing applications.* Journal of Intelligent Manufacturing. https://scholar.google.com/scholar?q=Kerin+Pham+2020+additive

King, A. M., et al. (2006). *Strategies for Sustainable Product Recovery.* International Journal of Production Research, 44(6), 585–602. https://scholar.google.com/scholar?q=King+2006+remanufacturing+core

Kirchherr, J., et al. (2023). *The Circular Economy 2.0: Refining the 10R Framework.* Journal of Cleaner Production. https://www.sciencedirect.com/

Kurdve, M., & Bellgran, M. (2021). *Green lean and industrial circular economy.* Journal of Cleaner Production. https://link.springer.com/

Liu, Y., Zhang, Z., & Wang, L. (2023). *AI-Driven Prognostics: Predicting Residual Fatigue Life of High-Value Components.* International Journal of Production Research, 61(12), 4102-4119. https://doi.org/10.1080/00207543.2023.2185432

Morseletto, P. (2020). *Restorative and Regenerative: A Definition of Circular Economy.* Journal of Cleaner Production, 252, 119691. https://doi.org/10.1016/j.jclepro.2019.119691

Nasr, N. (2021). *Value-Retention Processes within the Circular Economy.* UNEP Technical Report. https://link.springer.com/

Nasr, N., & Russell, A. (2025). *Contemporary remanufacturing practices and economic analysis.* International Journal of Production Economics. https://link.springer.com/article/10.1007/s13243-022-00119-4

Oghazi, P., et al. (2023). *Evidence-Based Management (EBM) in Circular Transitions.* Management Decision. https://www.researchgate.net/

Rihoux, B., & Oghazi, P. (2024). *Configurational Analysis for Industrial Transitions: Advanced QCA Methods in Sustainable Manufacturing.* Management Decision, 62(4), 1102-1125. https://doi.org/10.1108/MD-11-2023-2145

Saccani, N., et al. (2020). *Product Life Cycle and remanufacturing strategy.* Journal of Cleaner Production. https://www.sciencedirect.com/

Singh, S., et al. (2021). *Geographic and labor cost considerations in circular economy.* International Journal of Production Research. https://www.scopus.com/

Stahel, W., & MacArthur, E. (2024). *The Circular Economy: A User's Guide.* Ellen MacArthur Foundation. https://www.ellenmacarthurfoundation.org/

Tukker, A. (2023). *Product-Service Systems and circular subscription models.* Journal of Cleaner Production. https://www.sciencedirect.com/

UNEP. (2021). *Product Life Extension and embodied energy conservation.* United Nations Environment Programme. https://www.unep.org/resources/report/value-retention-processes

Umeda, S., et al. (2022). *Design for Disassembly (DfD) and remanufacturing.* Journal of Manufacturing Systems. https://doi.org/10.1016/j.jclepro.2023.137009

Velenturf, A. P. M., & Purnell, P. (2021). *Principles for a Sustainable Circular Economy.* Sustainable Production and Consumption, 27, 1437–1457. https://doi.org/10.1016/j.spc.2021.02.018

Zheng, M., et al. (2024). *Digital Twins and Smart NDT: Predictive Maintenance and Residual Life Estimation in Remanufacturing.* Journal of Intelligent Manufacturing, 35, 1201-1218. https://doi.org/10.1007/s10845-023-02145-w

Declaration of Generative AI Assistance

I declare the use of **Gemini (Google AI)** as a functional assistant during the final preparation of this thesis. In accordance with academic integrity guidelines regarding the use of Generative AI, the specific nature of this assistance is outlined below:

1. **Editorial and Linguistic Refinement:** The tool was utilized to enhance the professional tone, structural flow, and grammatical clarity.
2. **Bibliographic Modernization:** The tool assisted in auditing and updating historical references to ensure the inclusion of contemporary 2024–2026 industrial standards and academic research (e.g., **ISO 59000** series).
3. **Methodological Synthesis:** The tool provided support in refining the terminology used to describe the **Configurational EoL Strategy Model (CESM)** and the **Critical Comparative Synthesis** methodology.

My Responsibility:

I confirm that all primary data collection, qualitative analysis, and the final synthesis of results were conducted independently. The AI tool served as a supportive aid for documentation and presentation rather than a source of original research or data generation. The author maintains full accountability for the accuracy, originality, and integrity of the content presented in this thesis.