Development Of Optimized Cost Models for Recycling and Remanufacturing

- A Step Towards Circular Economy

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Foreword

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Note: The authors of this thesis have an equal contribution starting from the conceptional ideas to the final report.

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Abstract

Resource consumption is becoming increasingly scarce with an increase in the global population. Due to the increased resource consumption, the current linear economy model is unsustainable in the way it operates. The limitations of the linear economic model have been at the forefront to aspire circular economy in practice. Numerous factors have identified the need for the circular economy to emerge and mitigate the challenges over resource consumptions and environmental impact. A circular economy framework consists of various approaches to recover the materials from the end-of-life (EOL) stages. Over the decades, recycling and remanufacturing are the two primary practices that have been incorporated to recover the materials due to their economic and environmental benefits. Metals are the most consumable materials among the other materials. Metals are not consumable commodities like other natural resources. The statistic shows that every year million tons of metal waste are stagnating. Out of all the waste, although millions of tons of waste are currently being recycled and remanufactured, more can be done with an effective economic model.

This thesis aims to close the existing gap in the conceptual economic models. Furthermore, it focuses on developing an economic model for recycling and remanufacturing practices using economic and performance parameters with various cost (direct & indirect) considerations is involved in each stage of the respective process. The academic literature was performed to identify the key variables and stages involved in the process. The developed model’s framework was presented to aid the stakeholders in decision-making regarding all the aspects of the product life cycle. This model can be applied to all the metals to explore their post-recovery alternatives in the closed-loop stream. This model adds significant value to sustainable product development.

***Keywords**: Circular Economy, Economy Models, Recycling cost model, Remanufacturing Cost models, EOL treatments*, *Product life extension*

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Nomenclature

Circular Economy	CE
End of Life	EOL
End of Life Recycling Rate	EOL-RR
WEEE	Waste from Electrical and Electronic Equipment
E-Waste	Electronic Waste
MT	Metric Ton
WC-CO	Tungsten Carbide
EMF	Ellen Macarthur Foundation

1. Introduction

This introductory chapter illustrates the research area and outlines the background knowledge of this thesis and briefly states the hypothesis behind the present study and explores the problem definition to address the concerning research objective's and depicts the overview of this study.

1.1. The Need for Circular Economy

In today's rapidly changing global economy with the context of resource consumptions and decreasing resource supply, numerous concerns have been raised to meet the demand for future generations (Foundation, 2015). Governments and businesses are getting progressively worried about the growing pressure on global resources because of human activities (Russell, 2017). We started consuming all the available non-renewable resources and producing an extensive amount of waste by adopting a linear business model, which is also described as the "take-make-dispose" model. This current dominating model is not a sustainable way of producing products (Stahel, 2016). Our enormous usage of raw material and energy is stressing and damaging the natural system. This means we extract the materials and transform them into a product as economical as possible and use them for a while. When the product loses its functional and economic value, they are disposed as waste (Stahel, 2016) (Whalen, 2014). Due to this, there are shortages in critical supplies of resources, and few critical raw materials will be exhausted soon (Foundation, 2015). Further, Other consequences include the destruction of natural resources such as forests and lakes, toxic emissions, fluctuating commodity prices, increased demand for materials, geopolitical dependencies, or biodiversity loss (Rockström, 2009) (Braungart, 2002). The environmental problem has led to a debate about better approaches to sustainable business. Various factors suggest that the linear model in which it operates increasingly reaches its limits (McMichael, 2003). Enormous change is needed to keep the system stable. Wiser use of resources will further empower people to value a prosperous life on a healthy planet with a sound and sustainable economy (Geissdoerfer, et al., 2007). To overcome this, a Circular economy is required to make our resources much more circular so that we accomplish more by consuming less. The circular economy model offers a sustainable and resilient long-term arrangement that would close resource loops and return them to the mainstream (Foundation, 2015) (Stahel, 2016) (Braungart, 2002) (McMichael, 2003).

1.2. The Circular Economy

The idea of a circular economy (CE) has been developing for several years. It has become undeniably well known in the fields of sustainability, waste management, and economics (Bocken, et al., 2016). This concept is quickly gaining traction among academics, industrialists, and policymakers. However, there are many speculations about this concept. To address these speculations, let us first understand what a circular economy. CE has several definitions based on context, it aims to redefine natural-ecological growth and focus on the positive prospects of societal challenges. It seeks to rebuild capital to ensure an improved flow of goods and services through more efficient and effective solutions (Foundation, 2015). The supreme goal is to extend the life of products /materials and keep them as valuable as possible (Stahel, 2016). The circular approach illustrates the better use of resources. The strategy states that this can be done by either using the product longer or giving the product a new life using end-of-life (EOL) resources (Braungart, 2002).

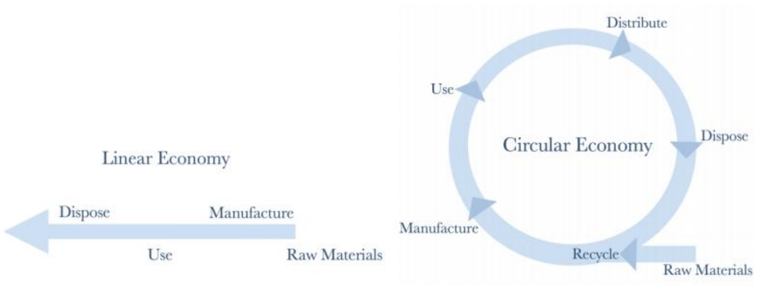


Figure 1: *Flow of resource utilization in the Linear model compared to the circular model as explained in* ***(Foundation, 2015).***

The transition from a linear to a circular model requires changes in economic and technological perspectives (Stahel, 2016). The circular economy is an industrial economic model that creates the possibility of a closed loop for companies. It implies a drastic change in the way business is conducted. The Ellen Macarthur Foundation (EMF) has elaborated on these challenges and illustrated that the transition to CE requires changes in strategies and business models, and the system in terms of manufacturing processes (Foundation, 2015). The circular model starts at the design stage (Nußholz, 2017). In this way, the accumulation of excessive resource use can be eradicated from the beginning to the EOL phases (Bocken, et al., 2016). It involves various activities such as reverse logistics, slowing down, and closing the flow of resources to eliminate waste (N.M.P.Bocken & short, 2016). This can be done by preventing the products from reaching the EOL stage and using the resources effectively. CE is based on the idea that there is no such thing as waste (Foundation, 2015). Crucially, the circular economy is much more than resource management. It is also about creating and executing circular products, designing business models, and formulating policies. Moreover, it is linked to the evolution of our standards and behaviour’s to build a circular society (Whalen, 2019).

According to EMF, materials must be kept in cycles from extraction and throughout their life cycle to minimize the flow of materials to landfills from an economic and material perspective (Oghazi & Mostaghel, 2018). Understanding the technical flow of materials from the butterfly diagram has highlighted the importance of closing the loops (N.M.P.Bocken & short, 2016). CE is not just about recycling waste. It is about changing the entire consumption system. This allows products to be used longer, repaired, refurbished, remanufactured, and eventually recycled (Ragossnig, 2019). Also, more reusable materials and products can be used in the manufacturing process to restore the capacity of natural resources. There are different ways to achieve the circular economy, not just one fixed strategy. Upgrading and reconfiguration are also considered as one of the ways to extend the life cycle (Stahel, 2016). Different options are recommended for alternative products depending on their condition (Hapuwatte & Jawahir, 2019). Concepts such as remanufacturing and recycling have gained popularity recently and are mainly guided by governments and organizations as part of the circular economy.

1.3. Need for Remanufacturing and Recycling

According to the Circularity Gap Report, the world is currently about 8-9% circular (CGRi, 2017). At this current rate, it is virtually and physically impossible to achieve CE. Low circularity rates are found in all sectors (Wieser & Tröger, 2018). Advances in technology have created new opportunities for waste prevention. To increase environmental protection and improve resource efficiency, companies are now increasingly aware of the benefits of closing the loop, such as saving material costs, creating competitive advantages, and accessing new markets (Bartl, 2014). Numerous barriers pose incredible challenges to the global economy (Kirchherr, et al., 2018). Small changes such as minimizing waste would only prolong a coming collapse of the current financial framework. Industrial production has spurred economic growth by increasing the rate of production, which increases consumption and thus waste (Murray, et al., 2017). According to reports, each citizen in the EU produces an average of half a ton of municipal waste in a year (commission, 2011). Let us assume that this continuous waste production reaches the threshold and harms the environment in terms of energy and landfill, and pollution (Braungart, 2002). The decoupling of waste generation requires a significant shift in developing new strategies to preserve materials with an economic value (Stahel, 2016).

Throughout the long term, the manufacturing industry has adopted advanced methods to address this challenge. The main concern here is when natural resources are running out as demand increases. How can the manufacturing industry rely on materials with a fluctuating material price, and how does the metal shortage affect economic growth? New strategies for reuse, recycling, and remanufacturing are emerging as a solution to the above challenges (N.M.P.Bocken & short, 2016). Inner loops give the most excellent value to the concerns of materials, energy, and sustainability. The concepts of 6R (Reduce, Reuse, Recycle, Recover, Redesign, Remanufacture) have been strongly influenced by the introduction of "closing the loop" (Jawahir & Bradley, 2016). The ability to extend the product life and recover resources at the end of their life is fundamental to securing future industrial activities.

Current remanufacturing, recycling, and reuse activities are focused solely on economic sustainability to meet the current competitive market (Reike, et al., 2018) (Nußholz, 2017).

1.4. Problem definition

Circular economy transition is a bifurcated and complex process that implies changes in strategies and business functionality (Whalen, 2019). Many researchers have highlighted the obstacles in the transition to CE and provided various approaches to the conservation of raw materials such as Life cycle assessment (LCA), green industries, and industrial symbiosis (Stahel, 2016) (McMichael, 2003) (Jawahir & Bradley, 2016). The characteristics of the world population and high standard of living have a far-reaching impact on economic growth and environmental issues worldwide (Rockström, 2009). The ramifications are the aftermath of the economic models of neoclassical economic sectors that have prevailed for decades (commission, 2011). There is an intense need to change the way resources are managed over the decades (Commission, 2007). This has resulted in a progressive, sustained debate about rethinking today's business opportunities and economic models.

Walter R. Stahel has presented a significant theoretical economic model for closing the loop on remanufacturing and recycling (Stahel, 2016). However, there is an excellent need for a practical economic model in the transition towards a circular economy. That is needed to be explored in the best possible way to be circular (Commission, 2007). In extending the life cycle of metals through remanufacturing & recycling, it is clear from the (Spoel, 1990) assessment although millions of metals are currently recovered and used each year globally, there is still much more to do to make this more economical (Reck & Graedel, 2012). It has been found that even more metals can be recovered and recycled if an appropriate economic model is presented (Spoel, 1990). This thesis will focus on closing the existing gap by developing a theoretical economic model.

1.5. Research Objectives

The idea of a circular economy has evolved over the past decade based on various schools of thought (Foundation, 2015). The vast majority of writings have explored the shift towards a circular economy on a large scale and at a micro-level, assessing the public benefits, distinguishing the boundaries and drivers towards one CE, and creating complete strategy systems to invigorate the execution of CE standards (Whalen, 2019) (Wieser & Tröger, 2018).

The major intent of this thesis is to identify the critical economic and performance parameters that exist in the recycling and remanufacturing process concerning the knowledge gap and to understand the theoretical and practical implementation of these concepts. This study will explore the opportunities for improving remanufacturing and recycling in terms of cost models. By addressing the below-mentioned research objectives, this research will aid in developing a holistic decision-making framework for both the remanufacturing and recycling industries to make better strategic decisions. This research will help address concerns related to sustainable product development.

RO. 1 Investigate the need for Metal Recycling and Remanufacturing.

RO. 2 Identify the critical economic and performance parameters involved in remanufacturing and recycling.

RO. 3 Develop an economic model for recycling and remanufacturing considering the economic and performance parameters.

The overall purpose of this study is a quantitative approach, as it aims to explore theory in a new context and contribute to the advancement of hypotheses in the field of sustainability. In any case, parts of the results should be considered from a positivist point of view. It is necessary to understand the economic and environmental benefits of remanufacturing and recycling.

1.6. Thesis Overview

This section illustrates the comprehensive overview of this thesis. This thesis comprises seven chapters. Chapter 1 depicts the motivation behind the research and formulation of research objectives. Chapter 2 specifies an overview of the theoretical and conceptional perspectives of metal conception and describes the need for a new approach to restore waste/ scrap through recycling and remanufacture. Chapter 3 & 4 comprehends major driving factors associated with the respective process and develops a cost model. Chapter five describes the results in terms of each activity and stages of recycling and remanufacturing. Chapter 6 includes a discussion about the results and flexibility of the model. Chapter 7 concludes and discusses the future scope of the models.

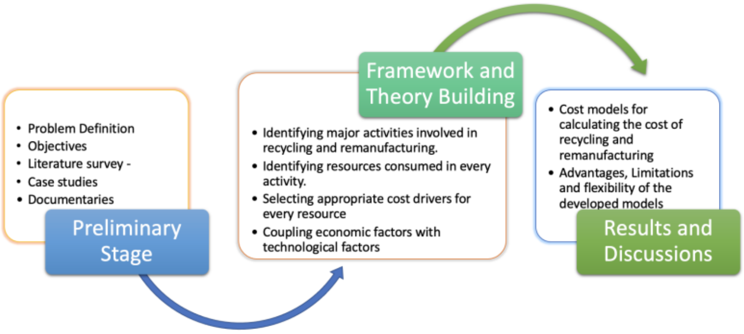


***Figure 2**: Structure of the thesis.*

2. Theoretical Framework

In this chapter, the research framework is presented. At first, the significance of metals is discussed, and further, it shows evidence that waste stagnation and practical measures are taken to preserve the resources. A literature review follows this to address the research objectives. At the end of the chapter, research objectives 1 and 2 are answered.

2.1. The Era of Materials

The production and consumption of natural resources are rapidly increasing (Hertwich, 2010). As the world consumes the materials extracted from the earth's crust, natural resources are depleting (Partha & Geoffrey, 2017). At the same time, new resources are constantly being designed. Humanity must begin to think about the practical and sustainable use of resources (Rockström, 2009). Metals have been among the indispensable components of our lives since the industrial age (Reck & Graedel, 2012). Due to their indispensability and versatility, they are all around us (Graedel, et al., 2011). The variety of applications of metals has increased in society depending on their properties. Metals are classified into different categories: ferrous, non-ferrous, base, technological, noble, and critical (Reck & Graedel, 2012). All groups of metals are indispensable and essential to modern society, irrespective of which group they belong to (Hagelüken, et al., 2016). Each metal has its own method of extraction and processing; at each step, the value of the material is increased in terms of time and energy (Wellmer & Hagelüken, 2015). Most industries rely on various metals due to mass applications, such as steel in construction, aluminum in automobiles, and many more innovative technologies. Metals and other raw materials are essential for our socio-economic development (Peck, et al., 2020). The demand for raw materials will increase as their applications penetrate the market (Peck, et al., 2020). It is imperative to provide such a large amount of materials and resources without disturbing the natural ecosystem (Reck & Graedel, 2012). The existing model is still a dominant way to manufacture and sell products (Commission, 2007). This can exacerbate scarcity conditions, create global instability to the national economy (GDP), and increase commodity prices (commission, 2011). Furthermore, other negative environmental impacts have led to the emergence of a discussion about better approaches to sustainable business (N.M.P.Bocken & short, 2016).

2.2. Metal Waste Handling

Metals are core for the global economy and are becoming increasingly important and critical to trade with a secure supply (Peck, et al., 2020). They are also becoming a challenge for society in shifting to low-carbon emissions, affecting their mining, extraction, and refining (Wellmer & Hagelüken, 2015). In the meantime, few metals have become critical due to their use (Reck & Graedel, 2012). Looking at metal used across the production chain, about 10 million tons of essential metal ores are needed to satisfy the user interest in Flanders (Belgium). Metal waste results from discarded materials or products with a monetary value that can be recycled when an obsolete scape reaches EOL. Corresponding to the Bureau of International recycling ferrous division, approximately 630 million tons of pre-and post-consumer steel scrap reaches the EOL. It is used as feedstock for recycling (Division, 2021). This saves about 950 million tons of Co_2 emissions, more than the Co_2 emissions of the entire EU transport sector per year (Division, 2021).

In addition, by saving energy and conserving natural resources. Using scrap as a raw material shows a solid commitment to environmental protection and reduces raw material prices & dependence on other countries (Peck, et al., 2020). It also allows for more effective management of waste (Guerrero, et al., 2013).

Currently, 23 billion tons of steel have been recycled since steel production (Association, 2021). Today, it is accounted that the global steel industry has used about 2 billion tons of ferrous metal, 1 billion tons of metallurgical coal, and 575 million tons of recycled steel to provide about 1.7 billion tons of robust steel (Division, 2021). Similarly, an estimated 1.5 billion tons of aluminum has been produced since 1880 (aluminium, 2021). The amount of secondary aluminum production from scrap has increased from one million to 20 million tons (aluminium, 2021). The policy is currently focused on waste management, but there is no such thing as waste in CE (Foundation, 2015). Waste and product policies need to be linked to the implementation of CE. (Whalen, 2014) However, these industries need to make extensive changes in policies, strategies, business, and economic models with new technologies (Bocken, et al., 2016).

2.3. Need for a New Approach

To optimize waste, a new approach such as the circular economy must be incorporated. The circular economy is an economic model that allows companies to create a closed-loop through reuse, recycling, and remanufacturing (Bocken, et al., 2016). It aims to close the gap between production and the natural eco-cycle by radically limiting raw material extraction, creating a waste-free product, and keeping the value of materials and components as high as possible (Foundation, 2015). Waste produced and resources used can be optimized (Russell, 2017). This can be achieved by keeping products in both technical and biological cycles (Foundation, 2015). In the technological cycle, the product life cycle is extended by the resolver framework or 3R (Reuse, Recycle, Remanufacture) methods (Stahel, 2016).

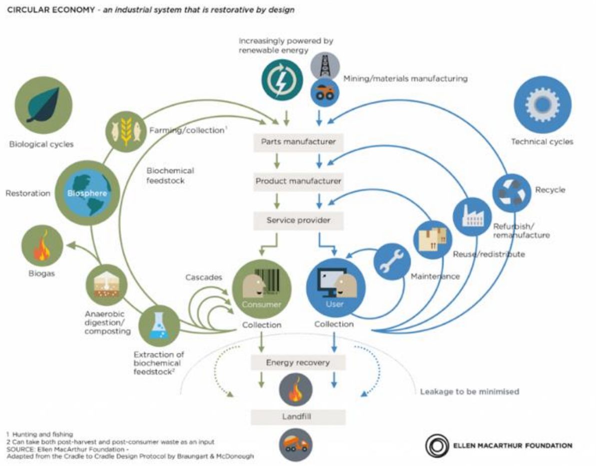


Figure 3: *Resources flow in the circular economy using butterfly diagram* ***(Foundation, 2015)***.

According to the EU Criticality Assessment, 61 raw materials were studied, of which 26 were assessed as critical raw materials for the EU; these materials have the highest economic importance with relatively high supply risk (Graedel, et al., 2011). The assessment has also provided insights into countries with secure supplies and their dependence on imports. Metals are not consumable commodities like other raw materials (Wellmer, 2015). The need for an effective material handling system arises from various concerns from both industry and policymakers (Geissdoerfer, et al., 2017). The hierarchy of waste management has developed a framework to manage waste most effectively through reuse, then recycling, energy recovery, and then landfill (Zhijun & Nailing, 2007). The circular economy concepts have emerged from interdisciplinary fields of sustainability such as industrial ecology (Richards & Allenby, 1994), cradle to cradle (Braungart, 2002), and biomimicry. It allows us to do what we could not do before, such as making products in a new way and helps us manage resources sustainably (Geissdoerfer, et al., 2007).

2.4. Methods for life extension

According to Walter R Stahel's: The Inertia Principle,

"Do not repair what is not broken, do not remanufacture if it can be repaired, do not recycle if it can be remanufactured" at TU delft (Stahel, 2021).

Extending product life is one of the critical concepts of the circular economy. CE requires long-lasting products (Lieder & Rashid, 2016). This can be achieved by returning products to the cycle through reuse, recycling, and remanufacturing (Lieder & Rashid, 2016). These cycles require a smaller number of resources than manufacturing the virgin material (Zhijun & Nailing, 2007). When done effectively, they result in more significant financial benefits (Lieder & Rashid, 2016). That is, the faster the metals reach the loop, the more savings in resources (material, energy, human capital) can be achieved (Whalen, 2019). Even in the circular product life cycle, there will still be material losses; we can limit the losses by recycling at each step (Sauerwein, 2019). CE is an activity that adds value to the product through the fundamentals of the triple bottom line concepts of sustainability and enables product life extension.

Figure 4: *Waste management framework* ***(Commission, 2021)***.

For many years, great efforts have been executed to reduce material losses and to put materials back into new material cycles. Most countries are now successful and able to recover materials from industrial waste and put them back into the production process (Bain, et al., 2010). Similarly, we can bring EOL products back to life by collecting and treating them in recycling facilities, but managing materials is not just about recycling (Hagelüken, et al., 2016). It is about managing the product or material life cycle. In response, sustainable manufacturing has evolved, intending to conserve resources and address life cycle sustainability issues. This can be achieved with the concepts outlined below (Bocken, et al., 2016).

2.4.1. Reuse

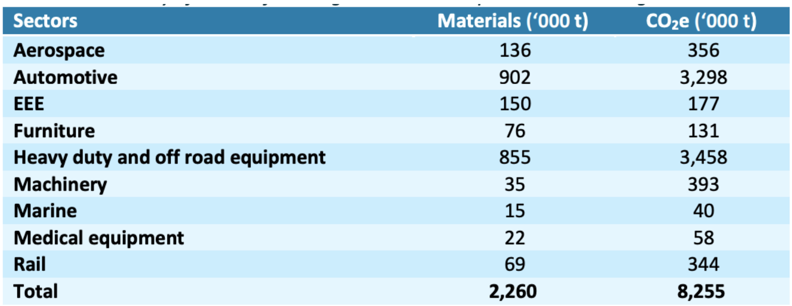
It is one of the most promising approaches to closing the material loop (King, et al., 2006). Reuse is when a product/material is used for a similar purpose without changing a product's physical form/property (Biswas, et al., 2013). Reuse occurs in various industries where it is technically possible to use it without compromising on safety (Nascimento, et al., 2019). The quality of

reused products is less than that of remanufactured & recycled products. The strategy for the reuse of some components is closely related to other features such as disassembly and reassembly. If the products cannot be reused, they are further sent for remanufacturing and recycling. However, this is a simple concept in itself but less used in practice (King, et al., 2006).
Further research is needed to understand this circular option (Stahel, 2016). In a Circular Economy, the reuse phase is considered in the early design phase of product development (King, et al., 2006). This allows products to be reused as quickly and effectively for different applications after their primary use.

2.4.2. Remanufacture:

Remanufacturing is a process of restoring durable, non-functional products to new ones. Many products are currently being remanufactured in various industries and home appliances (Schulz & Ferretti, 2011).
This process ensures that the energy used to manufacture the components is retained. The quality of the remanufactured product is equal to the newly manufactured products (Lund, 1985). Remanufacturing gives the products a second life and keeps the products in circulation. It helps in reducing the carbon footprint (Mitra & Webster, 2008). There is often a misunderstanding about remanufacturing and recycling. Remanufacturing is considered when a smaller amount of new material is needed to capture the value of the materials, and if a more significant number of materials are required, then it is not economically feasible to manufacture a product with reliability (King, et al., 2006). Remanufacturing is one of the most approached ways to stay ahead in the coemption market as it often results in reduced product prices in terms of material and energy. The products manufactured with remanufacturing are 40 -60% cheaper than new products (Bayındır, et al., 2007).

In terms of climate protection, remanufacturing is beneficial in that it reduces the use of raw materials and, therefore, energy consumption in production, which in turn reduces the carbon footprint in the environment (Liao, et al., 2018). Remanufacturing also produces less waste, which means less material has to be sent to landfills (Hasanov, et al., 2012). One of the reasons why remanufacturing is considered fascinating is that when a product is remanufactured, the geometric structure of the product is preserved, which is associated with economic value. Many environmental compressions have been collected and studied by (Sundin & Lee, 2012). This highlights the importance of remanufacturing from an ecological perspective. Less energy and material resources are consumed in many cases, and fewer greenhouse gasses are emitted than the traditional manufacturing process (Hasanov, et al., 2012). According to various studies, remanufacturing avoids emissions and saves many products from disposal; almost 80% of the material is recovered from the used products. In Europe, about 2.3 MT (metric ton) of material is saved from landfills, equivalent to 8.3 MT of the carbon footprint of various industrial sectors through remanufacturing, as shown in the figure below (Parker, et al., 2015).

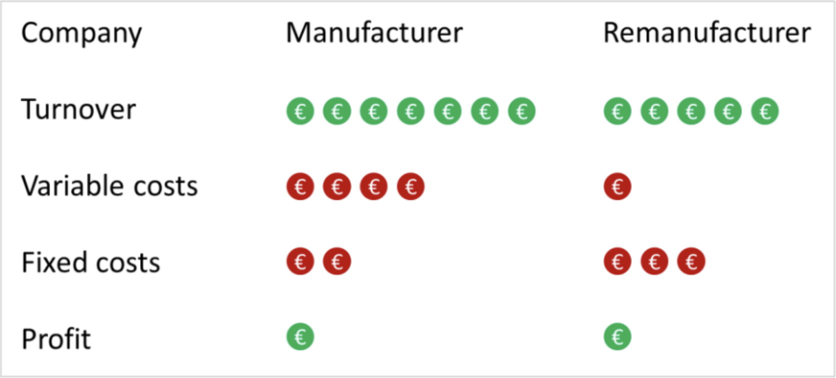


Sectors	Materials ('000 t)	CO_2e ('000 t)
Aerospace	136	356
Automotive	902	3,298
EEE	150	177
Furniture	76	131
Heavy duty and off road equipment	855	3,458
Machinery	35	393
Marine	15	40
Medical equipment	22	58
Rail	69	344
Total	**2,260**	**8,255**

Figure 5: *Amount of material and Co_2 emission saved in Europe through remanufacturing* ***(Parker, et al., 2015)****.*

The amount of material recovered annually by EU manufacturers is equal to the total mass of new cars registered in the UK. Similarly, the amount of Co_2 saved is equivalent to the Co_2 emitted in Belgium. Given the uncertainty of the carbon footprint for remanufacturing examined particularly and provides comfort in reality by saving millions of tons of Co_2 (Parker, et al., 2015).

Remanufacturing has a huge significance in achieving economic and environmental benefits (King, et al., 2006). Since the products produced in remanufacturing are more affordable than conventional products, there are normally higher margins of benefit on remanufactured things. The following table shows the main economic differences and similarities in terms of economics. The green marks show the profits whereas the red one shows the investments needed.



Company	Manufacturer	Remanufacturer
Turnover	€ € € € € € €	€ € € € €
Variable costs	€ € € €	€
Fixed costs	€ €	€ € €
Profit	€	€

Figure 6: *Economic representation of remanufacturing industries concerning manufacturing industry* ***(Parker, et al., 2015)***.

However, it is essential to remember that it should be manufactured first to remanufacture a product, and the other process has been carried out. The parts and the components which fail the quality test are sent to recycling rather than landfilling (Sundin, 2004).

2.4.3. Recycling:

Recycling is one of the last and essential steps to close the loop. It is one of the dominant ways to return materials to the cycle (King, et al., 2006). Recycling promotes the idea of closed-loop recycling to turn materials into use instead of waste (Commission, 2007). At the point when we recycle, used products are transformed into new products, which means fewer natural resources need to be devoured (Commission, 2021). If we do not use recycling methods, the products have to be made with raw materials that have a far-reaching impact on the natural habitat. According to UK waste statistics, recycling is estimated to save 18 MT Co_2 emissions per year

(Fisher, 2020). Using recyclable material consumes significantly less energy and reduces greenhouse gas emissions. The amount of electronic waste (E-waste) generated is rapidly increasing worldwide. To date, 49 million tons of E-waste have been generated (Forti, et al., 2020). This has a significant negative impact on the environment when it ends up in a landfill. For example, recycling one ton of cardboard can save 17 trees and 7000 gallons of water, and 165 gallons of gasoline (Anon., 2021).

Recycling provides numerous economic and social benefits. Recovering and reusing resources means conserving non-renewable resources (Bartl, 2014). Recycling is a cost-effective process. It can save up to 90% of production costs when recycled materials are used instead of raw materials (Geissdoerfer, et al., 2017). This is a work escalated process that requires a tremendous amount of staffing. Over the years, the recycling industry has managed to improve metal recycling and reassure the recycling of materials by importing scrap from other countries that dispose it in landfills (Guerrero, et al., 2013). Many recycling companies take recycling very seriously to produce zero waste sustainably (Hagelüken, et al., 2016). Metal recycling is one of them, as metals can be recycled infinitely without losing any physical properties. Metals are one of the critical raw materials that are essential for society and the ideal case for recycling. It is the most efficient method than extracting ores from mines. This does not mean that all metals are 100% recyclable. The recycling rate for metals can be determined in a number of ways (McMichael, 2003).

However, the standard approach is to determine the life cycle assessment of metals. Only 18 out of 62 metals have an end-of-life recycling rate (EOL_RR) of more than 50%, and three metals have an EOL-RR between 25- 50%. However, most metals have an EOL-RR of less than 1. Only 12% of the material comes from recycling. Using one ton of scrap steel saves more than 1100 kg of iron ore, 630 kg of coal, and 55 kg of limestone. It uses 40% less energy and emits 86% and 72% less waste dust than steel production based on virgin steel. Similarly, by using recycled aluminum, we can save up to 95% of energy compared to raw aluminum, reduce Co_2 emissions by 92%, minimize landfill options and give EOL metals a new lease of life (Graedel, et al., 2011).

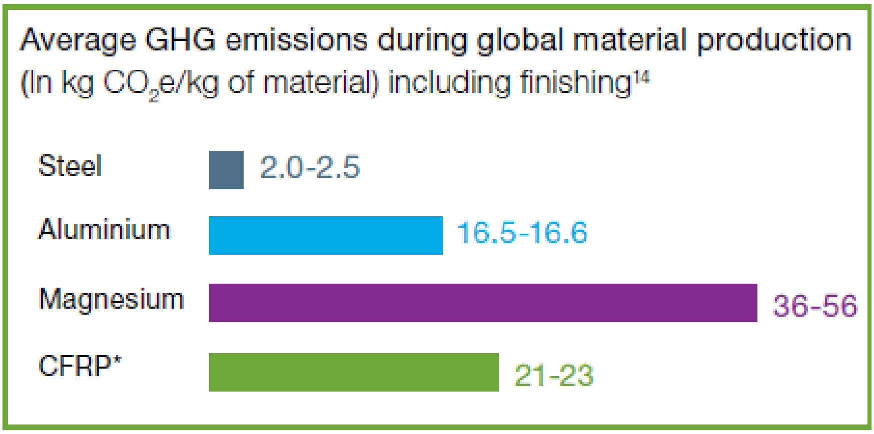


Figure 7: *Carbon emission of different metals* ***(Association, 2021)***.

European Union (EU) is the world leader in metal recovering and recycling from pre-and post-consumer scrap with its state-of-the-art recycling facilities (Marino & Pariso, 2020). Not just recovering, they are also leading in utilizing them in base metal production. Almost 50 % of the base metal production is carried out using recycling material in the EU, whereas the rest of the world accounts for 18% (Panel, 2011).

Considering the fact that the metal stock in the EU is growing and is accompanied by the expected development growth due to the greening of the economy, the recycling volume is expected to increase by 2050 due to the availability of a larger amount of used metals and the improvement of the overall recycling infrastructure (Graedel, et al., 2011). For example, annual aluminum recycling volumes in Europe are forecast to increase from 4.5 million tons in 2015 to 9 million tons in 2050.

In a sustainable future, new economic models are needed to increase the value of raw materials, which can be achieved by improving the practicalities of recycling and remanufacturing (Sundin & Lee, 2012). Emerging technologies can improve recycling and remanufacturing rates to minimize existing losses, resulting in the recovery of most materials from waste (Nußholz, 2017). Closing the loop can reduce the amount of waste that ends up in landfills. Similarly, raw materials and energy costs can be saved as reused materials can be used in new products. To achieve such promising results, we need an economic model that estimates losses and prices at each stage.

The above concepts have answered research objective 1 (Investigate the need for Metal Recycling and Remanufacturing) and provide a foundation for objectives 2 and 3. The next section explores the key economic and technological factors that form a solid foundation in recycling and remanufacturing to develop an economic model in relation to the research gap that more materials can be recovered if we have a proper economic model. This drives the search for the solution to research questions 2 and 3.

2.5. Literature review

2.5.1. Review for recycling

This literature review focuses on identifying the primary stages involves in the recycling and remanufacturing process and the key resources utilized in each stage of the process, and various crucial economic and performance parameters associated with the respective process.

Metals are substantial materials that can be reused over and over without debasing their properties (Reck & Graedel, 2012). Scrap metal has an important value in terms of economic and also environmental imperative. (Haque & Norgate, 2013) Therefore, metal recycling has become an essential process in sustainable resource management over the past few decades. (UN, 2020) with the initiative of UN sustainable goals, extensive research was carried out to understand the metal recycling process (Reck & Graedel, 2012) (Boom & Steffen, 2001) (Pauliuk, et al., 2013). The major focus was on environmental and cost benefits (Maung, et al., 2017). However, metal recycling in practice has a difference in comparison to theoretical (Graedel, et al., 2019).

Metal recycling is a complex and labour-intense process (Ignatenko, et al., 2008). Metal scrap ratios are increasing day to day. According to reports, around 2.2 million tons of scrap is generated in the US in the year 2018 (Agency, 2018). Every year almost around 400 million tons of metal get recycled all over the world (Anon., u.d.). At the worldwide level, steel scrap collection could cover 70% of steel production through recycling (Joly, et al., 2019). The metal scrap comes in various forms and shapes with mixed scrap quality. (Haupt, et al., 2017). Metal scrap can be classified into two types: ferrous scrap or nonferrous scrap (Maloney, et al., 2020). The key difference is among them is considered as the containment of iron in it. Generally, the scrap can be distinguished into home scrap, new (precomputed / prompt scrap), and old scrap (post consumed scrap) (Satyendra, 2017). Home scrap is generally generated during material production or fabrication. Pre-consumed scrap is produced during product manufacturing. Both the scrap has the highest purity and possess great economic value, and the post consumed scrap come after the consumer usage and the products that have reached EOL (Satyendra, 2017). Importantly metal scrap rarely comes in pure form. It is often alloyed with different materials for different applications (Reuter, et al., 2019). Due to this, metals often go for downcycling. For instance, high-quality steel from EOL cars becomes construction steel (Hertwich, et al., 2019). (Haupt, et al., 2017) concludes that the composition of scrap is varied substantially with in the total scrap in his research.

Scrap metal recycling includes few stages. It begins with the collection of scrap right from the miniature level. According to Eisted R, the scrap metal collectors collect small quantities of scrap (such as metal packaging cans), also known as kerbside collection, and sell to scrap yards, or the individuals can directly sell it to recyclers (Eisted, et al., 2009). In Carolina and Göran research, they have mentioned that the scrap collected from kerbsides is transported to the scrapyard (Liljenström, et al., 2015) and compressed or bailed before transporting to the recycling facility primary sorting was performed. It is estimated that a huge amount of ferrous scrap comes from the automobile industry. (Fitzgerald, et al., 2012). The scrap is then stored in the scrap yard and shipped to the large scrap dealers or the recycling facilities through various commodities such as rails, trucks, ships, etc. Fitzgerald says that transporting the metal waste to recycling facilities consumes fuel and resources (Fitzgerald, et al., 2012). The transportation distance will have an economic impact on the scrap (Eisted, et al., 2009). Collection rates fluctuate incredibly among various waste streams, contingent upon value, logistics, and different factors (Reck & Graedel, 2012). In fact, the waste from electrical and electronic equipment (WEEE) has relatively low collection rates despite the legislative effects (Maloney, et al., 2020). The collection rates greatly influence societal factors. Ghose has presented an effective way of collecting and transporting scrap in India (Ghose, et al., 2006). Terry Norgate has illustrated the energy consumption of each mode of the commodity used for the collection and transportation of waste (Norgate, 2013).

At some point, the product is no longer able to perform its functions. Then the product reaches the recycling facility. This doesn’t mean the product has reached EOL (Åkermark, 1997). According to Åkermark, sometimes it could be repaired and reused, or some of the parts are still functional. They are dismantled and sent to second-hand stores (Åkermark, 1997). Disassembly is required for the complex products where they possess sub-products more or less in a complex structure (Gentil, et al., 1998). Fugger says dissembling can be done both manually and automated (Fugger & Schwarz, 1999), automobile dismantling can practically be viewed as even to assembly (Gupta, et al., 1996). Similar to the assembly process, there are various specific tools and techniques required for dismantling reusable and unwanted products. (Coulter, et al., 1998). Kanari depicts in her study that in disassembly, time is one of the major factors that influence the cost, which in turn depends on the complexity of the products and mechanical constraints. The selection of tools varies from product to product. Suppose few tools are required to disassembly a part. It results in less price and time to disassemble (Kanari, et al., 2003). As Cui discussed, the level of automation is less in recycling, the process utilities more manual operators, and the usage of tools and the energy consumed by the tools adds up the cost (Cui & Forssberg, 2003). Dostatni concludes that the values of these resources used in disassembly are relatively low. Moreover, they are disregarded in calculating the total costs due to a lack of particular disassembly lines. In most cases, the cost of equipment, energy, and personal costs are used as disassembly costs (Dostatni, et al., 2014).

As Wright stated, the metal scrap that arrives at the recycling facility is pre-sorted at the local scrap yards (Wright, et al., 2002). Yet it contains various unwanted materials, which enable is the need for sorting and shredding, as argued by (Manouchehri, 2003). Home scrap and new scrap barely need any resources or operations in sorting apart from lancing the scrap into the desired chunk to fit in the furnace. (Odpadka, 2000) However, sometimes new scrap needs some of the operations to maintain the quality (Rem, et al., 2012). explain that post-consumed scrap such as automobiles, washing machines, rails, etc., requires manual sorting and a large number of staffing. Manual sorting is basically used to the products and materials that posse’s great value according to (Commission, 2002). Manual sorting clearly includes the separation of various mixed scraps by hand. It is most appropriate when various miscellaneous components (plastic tanks) are to be eliminated from the scrap. The detachment of metallics from non-metallics is likewise frequently achieved physically or using a magnetic separator (Bonifazi, et al., 2012). The magnetic separators are basically used to sort the ferrous materials from the rest, as explained by (Phillips, 2001). The importance of alloy sorting has been illustrated by (Ohno, et al., 2015). Various research studied the influence of automation in sorting (Sakr, et al., 2016), and various methods have been established to sort the scrap like eddy current separation (Rem, et al., 1997) (Yamane, et al., 2011). There are certain limitations for sorting, which are explained by (Gaustad, et al., 2012). (Rem, et al., 2012) concludes that high-quality recycling is only possible if sorting is done effectively.

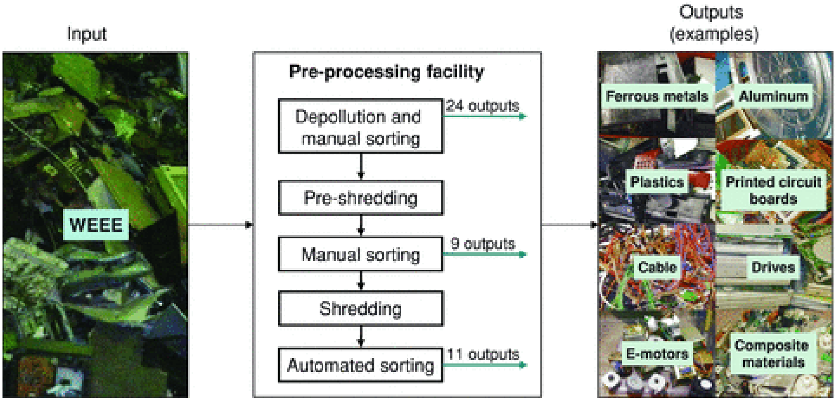


Figure 8: *Various types of sorting used in metal recycling* ***(Reck & Graedel, 2012)****.*

As the post-consumed scrap like automobiles, ships come in the desired shape they need to be shredded according to (Ohno, et al., 2015). Shredding is usually performed to tear the large pieces of scrap into small chunks so that the scrap takes less space in the conveyor belts. It makes it easy to handle scrap; hence the size of the scrap is reduced. (Jody, et al., 2011) argues that all home appliances have to be depolluted due to the risk of leaking chlorofluorocarbons. (Kanari, et al., 2003) adds that shredding will cause emission, and it will damage the surface treatment of the product. Zhao clarifies that sheading the scrap into tiny particles will help in melting the scrap faster and requires less energy (Zhao, et al., 2010).

The role of pre-processing is to get materials or segments in the right treatment and recapturing the materials from hazardous sub-stances such as oils and other toxic chemicals or other materials that are embraided on the materials (Khaliq, et al., 2014). The authors of (Odpadka, 2000) have illustrated that even after extensive sorting, some scrap contamination still exists in the form of debris and hazardous materials. Pre-processing also involves chemical modification of the materials, as said by (Meskers & Hagelüken, 2009). Lassner has illustrated various methods of recovering the scrap in his study, such as quenching the chlorides in water to extract tungsten carbide (Lassner & Schubert, 2012). Similarly,

Chancerel added that WEEE recycling also needs quenching and scrubbing to remove pollutant substances from it (Chancerel, et al., 2009). In some cases, metals need an additional process to recover the scrap material from its alloying elements or coated materials (Reck & Graedel, 2012). As explained by the authors in their study, the steel scrap attached with copper will go to the recycling stream. The presence of copper implies changes in the properties of the steel material and reduces the quality (Chancerel, et al., 2009) (Reuter & Van Schaik, 2008). To avoid this mishap, additional processing is required (Reuter & Van Schaik, 2008). Removal of such impurities is quite challenging in metals like WC-CO. They need an additional process in recycling, as discussed by (Furberg, et al., 2019) in chemical recycling conducts through the hydrometallurgy route and requires oxidation of tungsten scrap to make it solvable in alkaline solution (Leal-Ayala, et al., 2015). The usage of zinc recycling was explained by (Freemantle & Sacks, 2015). During recycling, the binder material cobalt will become alloyed with molten zinc from a porous cake. Here the zinc and the alkaline solution are considered as additional processes for WC-CO. As Shemi described, sometimes the metal scrap fails to meet the desired quality standards to be able to recycle. They have to undergo further conversion treatment process (Shemi, et al., 2018). The containments are removed through indirect recycling, as shown by (Furberg, et al., 2019).
Various other alternative methods were explored in indirect recycling by Takahashi and Yuize (Takahashi & Yuize, 1958) in chlorination method and Bhosale in sodium hypochlorite (Bhosale, et al., 1990). Lin adds that tungsten carbide scrap uses reagents during indirect recycling and the reagents are mainly NaOH, CaOH, $NaCO_3$, $NaNO_3$, and various organic and inorganic acids in the process. (Lin, et al., 1996) the authors have also stated that the lesser the usage of reagents is, the more sustainable and cost-effective process.

Lassner concludes that the lower the conversion steps it results in minimum the conversion cost and improves the efficiency of recycling (Lassner & Schubert, 2012).

The importance of scrap re-entry in the recycling process is explained by (Lassner & Schubert, 2012). He states that every manufacturing process will accumulate waste; similarly, the recycling process itself generates the waste. Branca adds that the waste has to be treated carefully due to its hazardous nature (Branca & Colla, 2012). The assessment on waste elimination by (Mauthoor, et al., 2014) has illustrated the waste produced in the recycling process. Corresponding to them, there are three types of waste: (i) slag, (ii) dust, (iii) sludge.

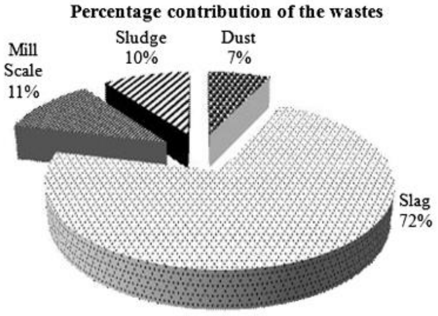


Figure 9: Different types of waste generated in metal recycling ***(Mauthoor, et al., 2014)***

(Wright, et al., 2002) have depicted that less than 100kgs of solid waste is generated in recycling per tonne of scrap in aluminum recycling. Similarly, (Branca & Colla, 2012) have presented the amount of solid waste generated in steel recycling. The authors have also validated the solid waste generation happens in each stage. The major solid waste in aluminum recycling is NaCl-KCL salt is currently being landfilled, as explained by (Utigard, et al., 2001). (Pereira, et al., 2000) argue that it can be used in refractories. The formation of slag in recycling was explained by (Wang, et al., 2012). Sludge formation usually happens in the casting process where iron oxides are formed on the metal surface, and they are removed by mill scale, also known as water spray, as depicted by (Murthy, 2012). To extract valuable materials from the slag, it has to undergo various processing technologies like crushing, leaching, etc. illustrated by (Shen & Forssberg, 2003). (Pickles, 2009) argues that dust is the major concern in metal recycling due to its hazardous nature. To recover the materials from dust, the primary process is Hydrometallurgical and pyrometallurgical that exist. Ding states that sludge processing is completely dependent on the iron present in the scrap (Ding, et al., 2011). If the iron content is low, then recovering materials is not economically feasible. The other alternative is safely disposing of it in landfills (Ding, et al., 2011).

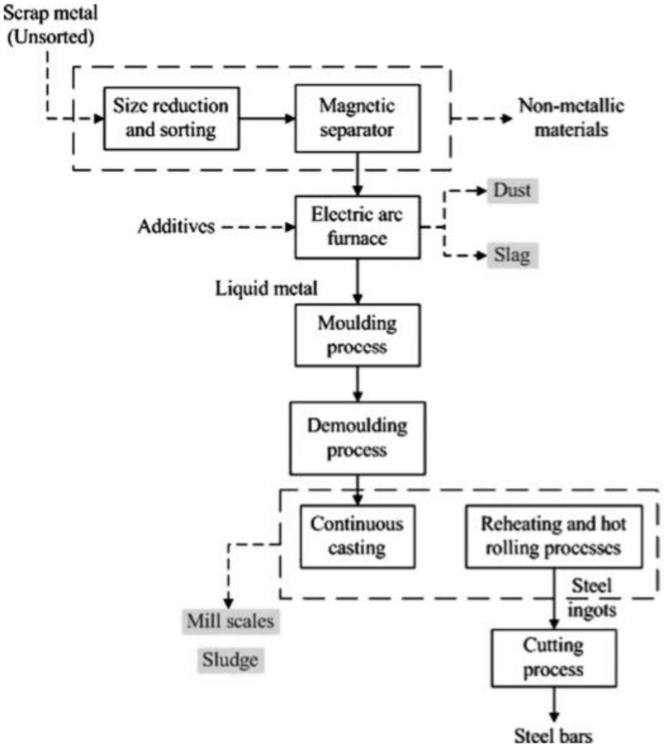


Figure 10: *Waste generated in metal processing* ***(Mauthoor, et al., 2014)****.*

Vieira has explored the opportunities for the sludge and determined that it can be recycled into red ceramic (Vieira, et al., 2006). Toxic metals like Hg, As, and Cd are barred from the acids and safely disposed of (Wright, et al., 2002). Hu has developed a model for handling waste treatment based on reverse logistics. He adds that there should be proper coordination between each stage to minimize environmental problems (Hu, et al., 2002).

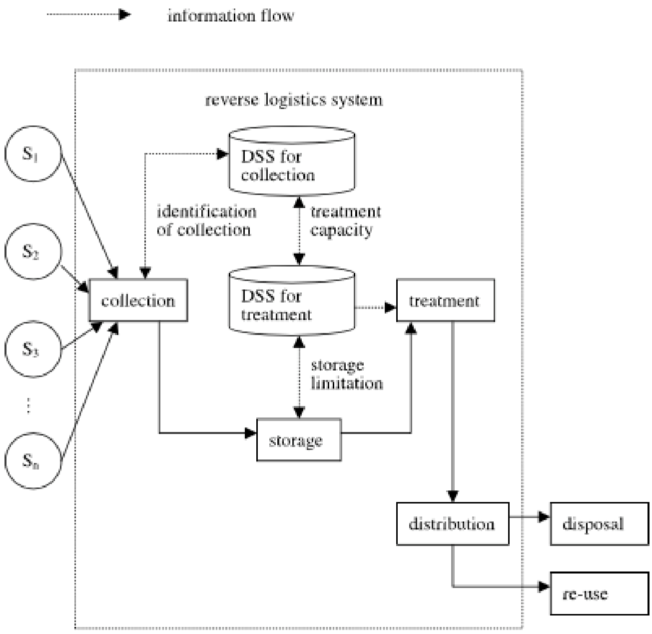


Figure 11: *Waste handing in the recycling process* ***(Hu, et al., 2002)***.

Apart from identifying the key parameters in each phase of recycling, this literature review has also presented key insights for model development. For segregating various kinds of metals, scrap is an important process in recycling. The author's mathematical expression has given a clear insight into the categorization of scrap in terms of x_1, x_2, x_3 (Bradley, et al., 2018).

$$\sum_{i=1}^{N_3} RRR_i = \left(\frac{x_1}{x_1 + x_2}\right)\sum_{i=1}^{N_1} P_i + \sum_{i=1}^{N_1} RMC_1 + TC + Z_i$$

Eq 1: *Equation for categorization of scrap* ***(Bradley, et al., 2018).***

Similarly, the expression for recovery costs expression shows the importance of transportation cost, and moreover, cost related to waste management is explained in his model (Bradley, et al., 2018).

$$\sum_{i=1}^{N_4} ES_i = LEC + WCM + HCS + Z_i$$

Eq 2** Equation for waste handling in recycling **(Bradley, et al., 2018).

2.5.2. Review for Remanufacturing:

Over the decades, remanufacturing practices have become an important activity in the production for many companies (Schulz & Ferretti, 2011). The evolution of remanufacturing was carried out from 1984 (Lund, 1985). Lund has illustrated the basic schematic of the recycling process in his study (Lund, 1985). According to (Georgiadis & Besiou, 2010), remanufacturing addresses the sustainable challenges and increases economic benefits (Giutini & Gaudette, 2003). According to (Network, 2020), remanufacturing is a product-specific operation. It varies from one industry to another industry (Network, 2020). Lund says that the remanufacturing steps and sequence are dependent on the product functionality (Lund, 1985). (Seitz, 2007) has depicted the importance of recovering EOL products in the automotive industry. (Seitz, 2007) states that the product recovery is increasingly gaining traction due to product take-back or buy-back options. Due to this large number of parts are parts are currently recovered and remanufactured (Brissaud, et al., 2006). It is often argued that remanufacturing is advantageous in comparison with other EOL treatments (Schulz & Ferretti, 2011).

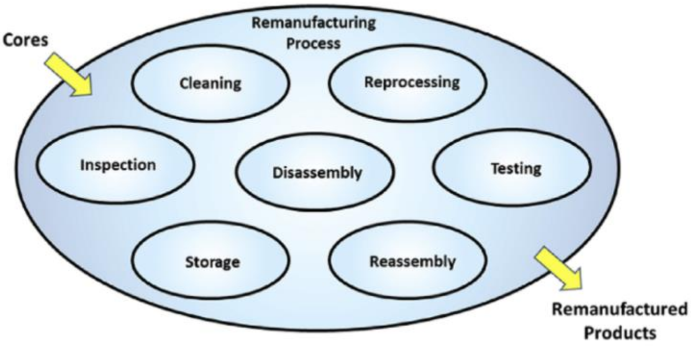


Figure 12: *Process involved in Remanufacturing* ***(Sundin & Dunbäck, 2013)****.*

According to (Sundin & Dunbäck, 2013), remanufacturing requires the collection of used products that can convolute the supply chain as it includes vulnerabilities of the product's quality and time. Lund adds that the used parts have to be durable and functional in order to be collected and remanufactured (Lund, 1985). Jayaraman says that the used product can come from various forms such as EOL or market stream in his study (Jayaraman, 2006). Sundin states that remanufacturing involves different stages in practice includes inspection, disassembly, reprocessing, reassembly, and testing (Sundin & Dunbäck, 2013). (Mähl & Östlin, 2007) second that. According to Seitz collection of used parts is one of the most crucial parts in remanufacturing to be able to satisfy the demand (Seitz & Peattie, 2004). A significant factor that should be viewed concerning the collection is original equipment manufacturers (OEM). Typically, OEMs have affiliates that recover EOL products or cores (Matsumoto & Komatsu, 2015). Recovering the EOL products from the customers and retailers has been studied by (Reimann, et al., 2019). Collection of this used part in an effective flow and storing them takes place by reverse logistics (Tibben Lembke, 2002). According to Chileshe, the collection of EOL material is quite a complex and intriguing process; it possesses several barriers (Chileshe, et al., 2016). Seitz states the collection process involves different actors like recyclers, customers, and OEM´s. This happens mostly in the automotive remanufacturing industry (Seitz & Peattie, 2004). Seitz says the collection can be well managed if the customers are aware of the retail network for replacement sometimes due to lack of knowledge, due to this, it is difficult to get access to cores in many cases, making it difficult for collection (Seitz, 2007).

(Awan & Liu, 2011) argues that the EOL products come from collection centers who are also known as retailers. However, (Alshamsi & Diabat, 2015) says that other firms will also collect the products from customers. (Awan & Liu, 2011) adds that the collection process consists of a primary inspection stage to ensure the quality of the product in his study. Alshami has described that if the product fails to match the quality standards, then it is sent out to other EOL treatments (Alshamsi & Diabat, 2015). Followed by transporting to the remanufacturing plant.

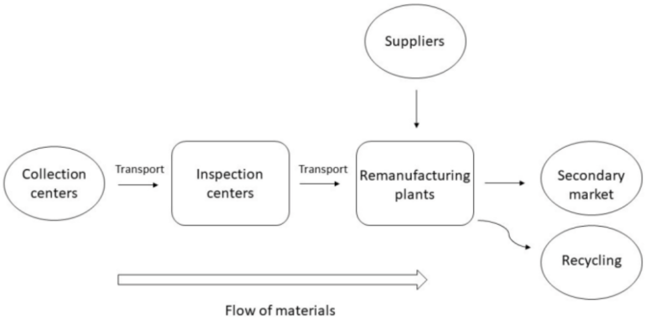


Figure 13: *Flow of products in the remanufacturing process* ***(Alshamsi & Diabat, 2015).***

The guide has depicted that inspection of used products is a time-consuming and labour-intense process. However, it can be streamlined by the use of sensors and other technologies (Guide & Van Wassenhove, 2002). The parts are inspected to assess the re-manufacturability. In contrast with product manufacturing, remanufacturing products require inspection all the time (Errington & Childe, 2013). The inspection is usually carried out on cores and disassembled parts, and reprocessed parts are stated by (Brent & Steinhilper, 2004). This is done to expand the second user's trust in remanufactured products, and it is thought to clarify why remanufactured

items seem to have preferred dependability over new products (Brent & Steinhilper, 2004). According to (Errington & Childe, 2013), there are three stages of inspection, (i) core acceptance, (ii) part inspection (iii) final inspection. The primary inspection is usually carried out visually on cores (Errington & Childe, 2013). The inspection time is similar for the same type of product. Based on the complexity of the product, the time varies (Errington & Childe, 2013). This determines that the products that are economically feasible will enter the process. The second phase of the inspection is carried out once the core has disassembled part inspection will be conducted to eliminate the non-reusable segments from the products (Errington & Childe, 2013). The parts might not be reusable due to some defect cracks, wear corrosion, etc., the result of the inspection determines the appropriate solution for the remanufacturing. The final inspection is performed to ensure that the products are fully
functional. The products that failed are revamped prior to being retested before entering the market (Errington & Childe, 2013). This cycle is often similar to the traditional manufacturing process (Lundmark, et al., 2009).

Contrasted with the manufacturing cycle, where disassembling in remanufacturing involves complete stripping down of core (Jiang, et al., 2016). According to Ikeda, the methods used for dismantling a product without breaking is an important factor for remanufacturers. A survey conducted by (Hammond, et al., 1998) says that disassembly is one of the major concerns in remanufacturing. Hatcher says that disassembly is a manual process due to various reasons, as explained in his study (Hatcher, et al., 2013). However, the author argues that manual dismantling is cost-effective due to the complexity of product design which is time taking and results in high operation costs (Jiang, et al., 2016). During the disassembly, each unit is disassembled into respective modules, this process generally involves various power tools, and in some cases, assistance from a robotic arm is required to dissemble complex products (Steinhilper, 1998). According to Gungor’s investigation, the damaged parts affect the disassembly process. It requires complete disruption of the product (Gungor & Gupta, 1999). Some complex products come with more joints; this means more time is required to dismantle the products, which reduces the economic value of the product (Zwolinski & Brissaud, 2008). Once the core is disassembled, then cleaning the components through the chemical spray technique is adopted. (Xu, et al., 2016).

According to (Andrew Munot, et al., 2015), during the reprocessing, the defective components are replaced with new ones. Component replacement is very critical in remanufacturing. Sometimes the remanufacturing component might differ from one product to other due to the uncertain quality of the used products (Andrew Munot, et al., 2015). (Sundin & Dunbäck, 2013) says that the number of reprocessing steps and required time is dependent on the quality of the product. The defects that are detected in the inspection can be an accomplice in this stage through various machining operations (Chmielewski & Golański, 2015). Other operations like welding and the material additive process can be adopted to restore the damages in the parts and reduce distortion, according to (Kin, et al., 2014). The enormous assortment of welding methods accessible for application in the recovery of surfaces gives the capacity to choose the right interaction in basically every area of utilization of the remanufacturing process (Chmielewski & Golański, 2015).

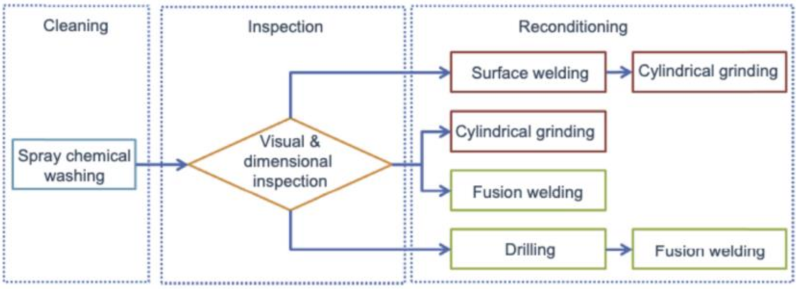


***Figure 14**: Types of recondition process in remanufacturing **(Xu, et al., 2016)**.*

According to (Andrew Munot, et al., 2015), once the parts are reprocessed, then they are transferred to assembly. This process is similar to the disassembly process, where various tools are used to fix the parts into a product. In some cases, it is mandatory to use robotic arms for complex products to be assembled (Steinhilper, 1998). (Xu, et al., 2016) has identified various costs involved in the remanufacturing process.

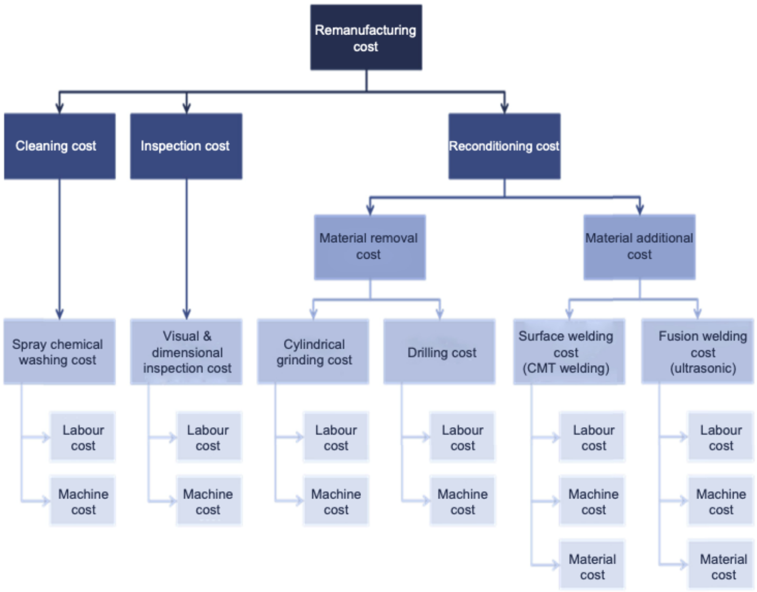
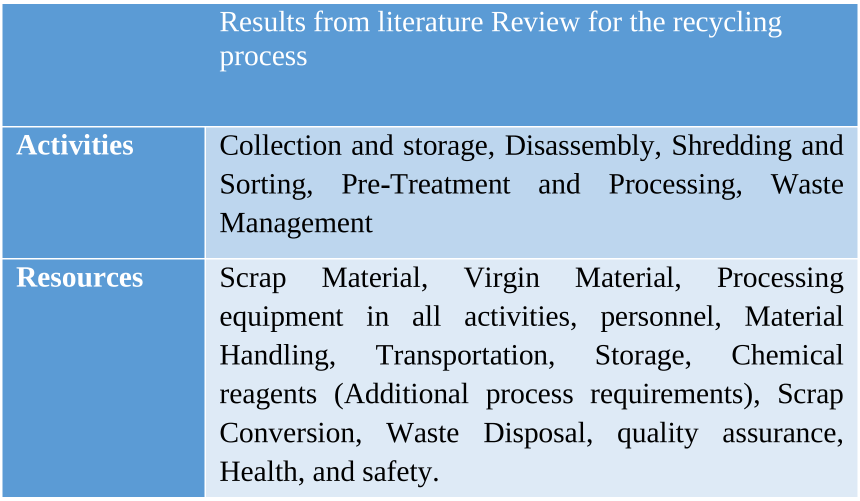


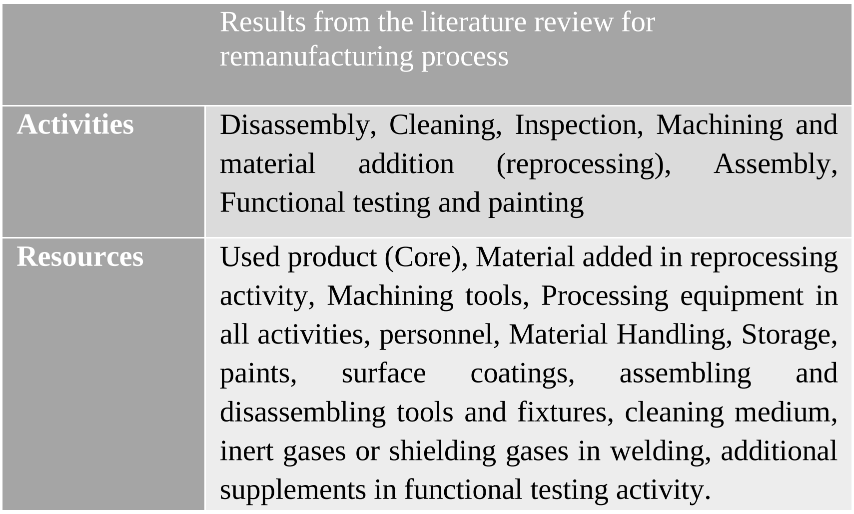
Figure 15: *Illustration of various costs involved in remanufacturing* ***(Xu, et al., 2016)***.

The above literature review has provided us with ample insights on both recycling and remanufacturing. Through the literature review, we have identified the key stages involved in the process and the major factors that affect this process, which address the **research objective 2** (Identify the critical economic and performance parameters involved in remanufacturing and recycling). The below table summarizes the key stages and important factors involved in each process. The below key findings form a base for developing a cost model of recycling and remanufacturing.



	Results from literature Review for the recycling process
Activities	Collection and storage, Disassembly, Shredding and Sorting, Pre-Treatment and Processing, Waste Management
Resources	Scrap Material, Virgin Material, Processing equipment in all activities, personnel, Material Handling, Transportation, Storage, Chemical reagents (Additional process requirements), Scrap Conversion, Waste Disposal, quality assurance, Health, and safety.

Figure 16: *Key findings from the literature review for recycling.*



	Results from the literature review for remanufacturing process
Activities	Disassembly, Cleaning, Inspection, Machining and material addition (reprocessing), Assembly, Functional testing and painting
Resources	Used product (Core), Material added in reprocessing activity, Machining tools, Processing equipment in all activities, personnel, Material Handling, Storage, paints, surface coatings, assembling and disassembling tools and fixtures, cleaning medium, inert gases or shielding gases in welding, additional supplements in functional testing activity.

Figure 17: *Key findings from the literature review for remanufacturing.*

Recycling and Remanufacturing processes adds some value to the given input material by consuming various resources therefore they are being considering as production process. Due to an extensive gap in the literature for technological factors in recycling and remanufacturing. Therefore, considering Cycle time, downtime losses, production rate losses, actual processing time, batch size, and setup time in terms of production perspective, (Ståhl, et al., 2007) (Windmark, et al., 2012).

2.6. Outline for developing a cost model.

Various economic and activity-based cost models are suitable for calculating the manufacturing cost of goods sold depending on the costing philosophy of the firm. Nevertheless, there have been very few economic models for calculating the cost of recycling and remanufacturing. The existing models are the summation of various direct costs involved in the recycling and remanufacturing processes. But none of these models have explained the indirect costs, various activities involved in recycling and remanufacturing, important resources required for various activities, and technological factors related to the processes. To fill this gap, this study focuses on understanding the standing cost models in manufacturing (Ståhl, et al., 2007). Based on the main findings, and economic models are developed regarding the activity-based cost model and the basic economic model for assessing production development.

The activity-based costing model (ABC) was developed by Cooper and Kaplan to deal with the complexity of allocating overhead costs (Cooper & Kaplan, 1991). In general, the ABC model is much more complex as it allocates various overhead costs used during the process. In terms, it helps to calculate the production cost by allocating the cost to each activity that goes into production rather than cost centres total cost.

This model first identifies all the major activities involved in a process and then focuses on the resources required in each activity. The costs (direct and indirect) associated with all the resources in an activity are considered, and an appropriate cost driver is selected. Finally, the costs of all activities in a process are summed to determine the production costs that are allocated to a product (Cooper & Kaplan, 1991).

Similarly, the basic economic model for assessing production development considers the influence of various production technological factors on the production cost of a part. This model considers various technological factors that can be weighed against each other (such as production rate losses, downtime losses, setup time, cycle time, etc.) and links them to the direct costs incurred in the manufacturing process (Windmark, et al., 2012). This allows the manufacturing industry to explore different product development scenarios and their impact on manufacturing costs. Based on the manufacturing-related development goals, the manufacturing industry can make an appropriate decision.

As mentioned earlier, the developed economic models for recycling and remanufacturing are based on an activity-based cost accounting model and a basic economic model for assessing production development. Like the ABC model, these developed models focus on the main activities and identify the resources involved in the activities. An appropriate cost driver (e.g., cost/hour) is selected. Then these cost drivers are coupled with technological factors associated with the processes as explained in the basic economic model for assessing production development. In this way, these developed models help calculate the costs associated with a particular activity, the total cost of recycling per ton, the cost of remanufacturing per product, and help in decision-making during product development. These models take into direct account costs, indirect costs (related material storage and handling), and technological factors (such as production rate losses, downtime losses, setup times, etc.) that form the basis for decision-making during product development.

3. Developing a cost model for recycling

This chapter explains various activities and their associated costs involved in the recycling process, various technological or performance factors considered in the recycling process. It explains appropriate cost drivers for different resource groups.

3.1. Foreword

As explained in the literature review, the cost of recycling is calculated by aggregating the costs incurred in each activity with which the scrap material interacts. Thus, in each activity, the cost of the resources used is considered, and an appropriate cost driver is chosen. Then, these cost drivers or economic factors are coupled with performance factors as described in the basic economic model for assessing production development.

Founded on the literature review, we found **five** primary activities in the recycling process. They are **collection and storage, dismantling, shredding and sorting, pre-treatment and processing, and waste management**. Section (**3.2)** explains all these activities and their associated costs in detail. Similarly, production rate losses, downtime losses, set-up time, cycle time, actual processing time, planned production time, and recycling efficiency are the leading technological factors identified and explained in detail **(3.3).** Section **(3.4 below)** explains the corresponding cost drivers and units chosen for different resource groups.

3.2. Major activities in the recycling process and their associated costs.

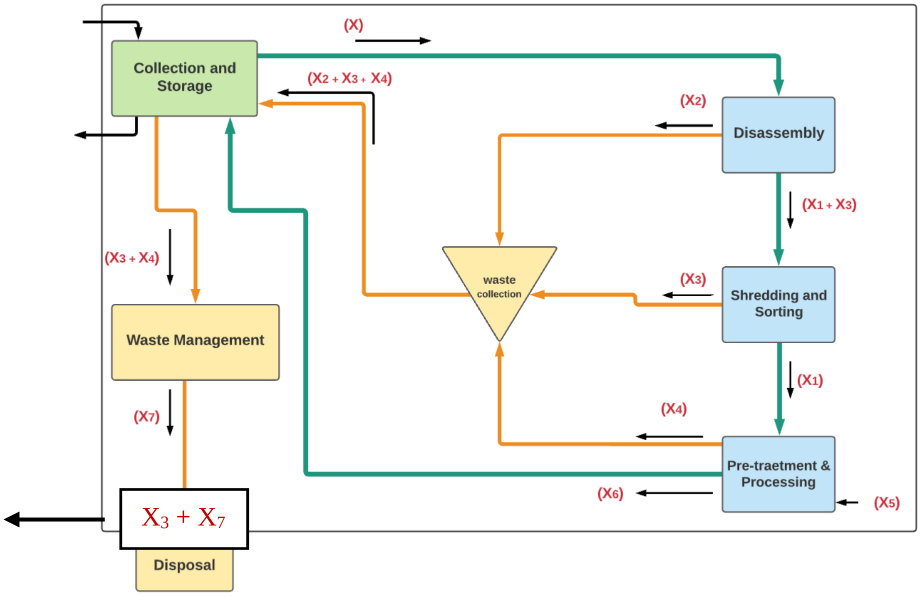


Figure 18: *Flow chart for the recycling process.*

3.2.1. **Collection and storing (K_1) – (Activity 1):** The recycling process begins with this activity. In this activity, special recycling trucks collect the scrap and transport the collected scrap to the recycling plant.

Then all the collected scrap is stored in the warehouse of the recycling plant. From this warehouse, the required amount of material is transported to the following processing step - disassembly.

- The collected scrap can be complex products like automobiles, refrigerators, or it can also be a high-value scrap from the machining operations in a manufacturing industry. Based on the collected scrap material few parameters can be neglected, as explained in section **(5.1.3).**

Major Resources -

- Since the dedicated recycling trucks will collect the scrap and ship it to the recycling facility, the costs associated with the trucks and personnel must be considered.
- In general, the collected material will not be processed at once. It has to be stored in the warehouse for a while. The costs associated with the storage have to be considered.
- Depending on the scrap type, the cost of the scrap material varies. The recycler has to bear the cost of scrap material.

Therefore, the major resources involved in this activity are Scrap material, Transportation, personnel, and storage.

The cost for collection and storage activity can be calculated as

$$K_1 = K_{Scrap\ material} + K_{Transport} + K_{Personnel} + K_{storage.} \qquad \textit{Equation 1}$$

3.2.2. **Disassembly (K_2) – (Activity 2):** This is not a mandatory activity for every recycling plant. Based on the type of scrap collected, this activity will be chosen. Mostly, this activity is applicable for the recyclers dealing with complex products like automobiles, refrigerators, computers, etc. Before recycling, the products will be disassembled, all the reusable parts (X_2) are collected and sent to the storage yard. From there, it is sent to appropriate manufacturers.

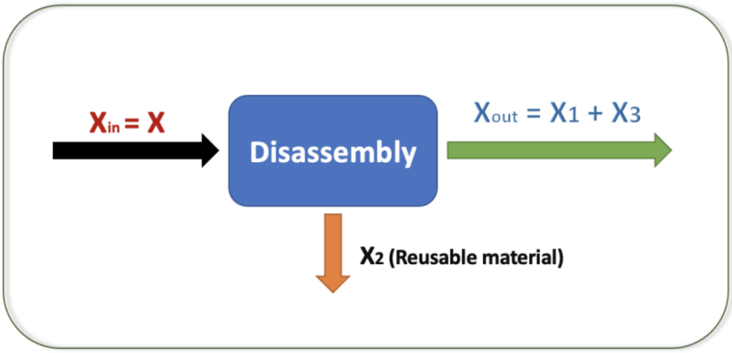


***Figure 19:** Flow of material in recycling disassembly.*

Major Resources –

- In this activity, the complex products have to be disassembled. Based on the complexity and type of the product, the disassembly can be either manual or automatic. In both, the disassembly processes, appropriate fixtures, and tools are required to dismantle the product. The costs associated with personnel and equipment have to be considered.

The major resources involved in this activity are equipment and personnel.
The cost for disassembly activity can be calculated as

$$K_2 = K_{Equipment} + K_{Personnel} \qquad \text{Equation 2}$$

3.2.3. **Shredding and Sorting (K_3) – (Activity 3):** From **Activity 2**, after eliminating the reusable parts, the remaining material is transferred to this activity, where it is shredded into small chunks. In **Activity 2**, only the reusable material is separated, but the product contains various materials like plastics, glass, composites, and metals. Now all these materials have to be sorted to get the desired material (metallic scrap). The shredding process is followed by a sorting operation. After sorting, the desired material (metallic scrap) is sent to the next processing step, and all the unwanted material (X_3)

(plastics, composites, glass and other metals, etc.) is collected and sent to the storage area as shown in the **Figure 18**.

Even the collected scrap is a high-value scrap from the machining operations in the manufacturing industry or from a scrap dealer who sells the sorted scrap, the scrap material has to pass through this activity to maintain the purity and the particle size of the scrap before entering into the furnace.

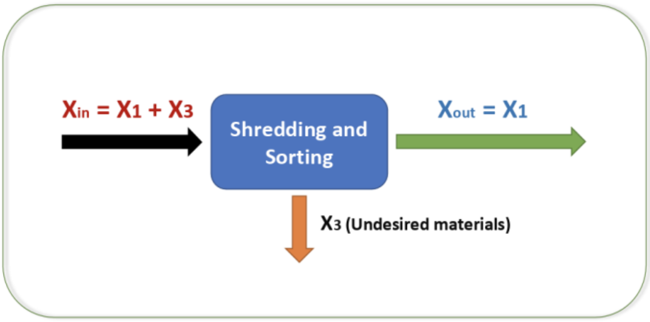


Figure 20: *Flow of material in recycling shredding and sorting.*

Major Resources-

- In this activity, for shredding the scrap into small chunks, equipment like double shaft shredder machine and for sorting the scrap, equipment like magnetic separators, X-ray separators, color camera sorting equipment, etc., are required. The cost associated with this equipment has to be considered.
- Generally, while loading and unloading the equipment and monitoring the process, the presence of personnel is a must. The cost of personnel has to be considered.

The major costs involved in this activity are equipment and personnel.

The cost for Shredding and Sorting activity can be calculated as

$$K_3 = K_{Equipment} + K_{Personnel} \qquad \textit{Equation 3}$$

3.2.4. **Pre-treatment and Processing (K_4) – (Activity 4):** From **Activity 3**, all the desired recyclable material (X_1) is transferred to this activity. Here the recyclable material goes through a pre-treatment process in which all the contaminants like grease, oil, Etc are eliminated. In some recycling processes, the pre-treatment stage is used for converting the scrap material into intermediate compounds. For example, in the indirect recycling process of tungsten carbide (WC), nitrate salts are used for converting WC scrap into Sodium tungstate during the pre-treatment stage, which can be readily solubilized in water.

After Pre-treatment, the material will go to the heating chamber in which it is heated to the desired temperature, and a quality inspection follows it. Based on the results of quality inspection, recycling efficiency, and amount of solid waste generated, a suitable amount of virgin material (X_5) is added to the recycled material to get the desired quality. From here, the molten material (X_6) is formed into various shapes like bars, blocks, Etc.

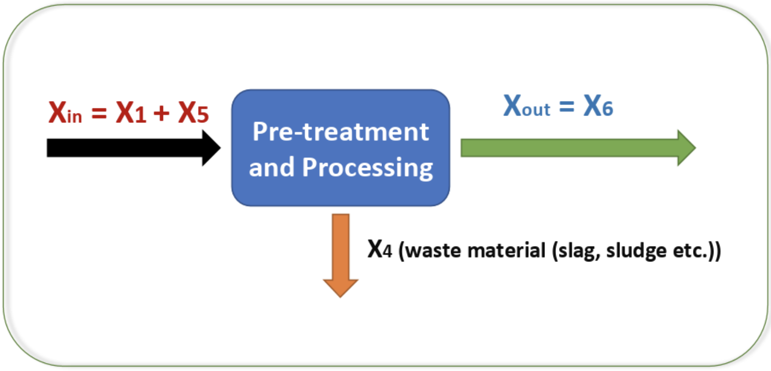


Figure 21: *Flow of material in recycling pre-treatment and processing.*

Major Resources:

- During the pre-treatment stage, appropriate equipment is required for cleaning the material or converting the material into intermediate compounds. Similarly, based on the type of material, the appropriate melting furnace is required, and after melting, the material is formed into bars and blocks. For this metal forming operation, appropriate forming equipment is required. The cost of all the equipment has to be considered.
- Depending on the recycling material, the recycling process consumes reagents for converting the scrap metal into intermediate compounds, which are then processed to obtain pure metals. In this cost model, these chemical reagents are considering as additional process requirements (APR).
- Sometimes, the scrap does not meet the desired requirements and specifications. The scrap will be re-entered into the recycling process by making some conversions. In some recycling processes, intermediate compounds have to convert into desired metal by passing through several conversion steps. The costs associated with these conversion steps are considered as conversion costs.
- Due to the involved conversions and chemical reactions, there will be a loss of a considerable amount of desired material in the form of solid waste (slag). So, this loss is considered under recycling efficiency, which is explained in section **(5.1.3)**
- During processing**,** based on the results of quality inspection, recycling efficiency, and amount of solid waste generated, a suitable amount of virgin material (X_5) is added to the recycled material to get the desired quality. The cost of virgin material added also has to be considered.
- At every step in this activity, personnel must handle the equipment and monitor the process. The costs associated with the personnel have to be considered.
- The waste generated in this activity (Slag, sludge, hazardous waste, etc.) has to be collected and stored before treating it. The formed material will be sent to the warehouse either for storing it for a

certain period or for sending it to the customer. The cost associated with the storage of waste and formed material has to be considered. The major resources involved in this activity are equipment, personnel, additional process requirements, conversion costs, virgin material, and storage.

The cost for Pre-treatment and processing activity can be calculated as

$$K_4 = K_{Equipment} + K_{Personnel} + K_{APR} + K_{conversion} + K_{virgin\ material} + K_{storage}$$

Equation 4

3.2.5. **Waste Management (K_5) – (Activity 5):** In the recycling process, various kinds of wastes are generated at various stages. All the waste must be collected, stored, treated, and then transported to appropriate reuse and recycling facilities or disposed of in a landfill. Depending on the type of waste, appropriate treatment methods are chosen at this stage.

In Activity 2, after disassembly, all the reusable parts are collected and stored. Later all the reusable components are transported to appropriate manufacturers.

In Activity 3, after sorting, various materials (Non-metallic and non-desired metals) are collected and stored. From the storage area, they are shipped to the waste management center. In this center, further sorting is done to separate the recyclable material from non-recyclable material. From here, all the recyclable material is transported to appropriate recycling facilities, and the non-recyclable materials are transported for disposal.

In Activity 4 various kinds of waste like slag, sludge, hazardous gases, mill scale, etc., are produced. For example, in the steel recycling process, the reactions between carbon, silicon, manganese, and some liquid iron oxides form oxidized compounds that react with dolomitic lime to form slag. Similarly, during the steel melting process, the volatile components are fumed off and collected with particulate matter in the off-gas cleaning system, which results in hazardous electric arc furnace dust. While forming the molten iron metal into bars and blocks, iron oxides are formed on the surface of the metal, and these are removed by spraying water on the metal, which results in a Mill scale. Also, when the suspended particles in wastewater from the steel production process settle down, then sludge is produced at a rate of 20kg per ton of steel. Depending on the waste type appropriate treatment method is chosen to recover the material and reduce the effect of waste on the environment after disposing of it.

Major Resources:

- Depending on the type of waste, appropriate treatment is chosen for treating the waste with appropriate equipment. The cost associated with the equipment has to be considered.
- Depending on the type of waste, the selected treatment method consumes reagents to minimize the impact of waste on the environment and recover the material. As mentioned in **Activity 4**. In this cost model, these chemical reagents are considering as additional process requirements (APR).
- Generally, after processing based on the type of waste material, it will be transported to other recycling facilities or disposed of in a landfill. Transportation and associated disposal costs (while disposing of in landfill) have to be considered.
- In every step in this activity, personnel must monitor the process and handle the processing equipment and transporting equipment. The costs associated with the personnel have to be considered.

Major resources involved in this activity are equipment, personnel, additional process requirements, transportation, disposal cost, and storage cost.

The cost for waste management activity can be calculated as

$$K_5 = K_{Equipment} + K_{Personnel} + K_{APR} + K_{Transportation} + K_{Disposal}$$

Equation 5

In this section, we can see that transportation costs are involved in multiple activities. Similarly, the costs associated with material handling between all the activities and between the storage and various activities have to be considered. Calculating these costs for every activity makes the model more complex by demanding more data. Instead of calculating these costs for every activity where they are involved, we calculate them for the whole recycling process, as explained in section **(5.1.5)** That is why we are eliminating the cost of transportation from collection and storage and waste management activities and adding them separately as shown in Equation **8**.

Therefore, the equation for calculating the cost for collection and storage activity and waste management activity can be written as:

$K_1 = K_{Scrap\ material} + K_{Personnel} + K_{storage.}$ *Equation 6*

$K_5 = K_{Equipment} + K_{Personnel} + K_{APR} + K_{Disposal.}$ *Equation 7*

In this section, there are various costs associated with various activities. For simplification, we classified all the costs into two categories as shown in **Table 1 -** Direct costs and Indirect costs.

Table 1: *Key resources and their associated costs in various stages.*

Activity	Resources	Direct Costs	Indirect costs
Collection and Storage	Scrap material Transportation Personnel Storage Material Handling	Scrap Material Personnel	Transportation Storage Material Handling
Disassembly	Equipment Personnel Material Handling	Equipment Personnel	Material Handling
Shredding and Sorting	Equipment Personnel Material Handling	Equipment Personnel	Material Handling

Pre-treatment and Processing	Virgin Material Equipment Personnel Storage APR Conversion costs Material Handling	Virgin - Material Equipment Personnel	Storage Material Handling Conversion costs APR
Waste Management	Equipment Personnel Disposal APR Transportation Material - Handling	Equipment Personnel	Transportation Material Handling Disposal APR

- Direct cost - is considered the cost directly related to producing goods or value addition to the product. For example, cost of raw materials, the salary of personnel, equipment cost, Etc.
- Indirect cost – these are the costs that cannot be directly linked to the product, but the presence of these costs is mandatory, and these costs neither add any value to the product nor generates revenue—for example, storage costs, material handling cost, etc.

However, along with the indirect costs mentioned in **Table 1**, some other hidden indirect costs in the recycling process have to be considered, and these costs are considered additional costs. The costs associated with quality assurance, health and safety, and any activity-specific indirect costs (like local storage or buffer cost, forming tools cost, etc.) are considered under additional costs, explained in detail in section **(5.1.7)** Similarly, calculating these costs for every activity making the model more complex by demanding more data. Instead of calculating these costs for every activity in which they are involved, we calculate them for the whole recycling process, as explained in section **(5.1.7)**

Therefore, the total cost for recycling ($K_{Recycling}$) a ton of the material can be calculated as

$$K_{Recycling} = K_1 + K_2 + K_3 + K_4 + K_5 + K_{Material\ handling} + K_{Transportation} + K_{Additional}$$

Equation 8

3.3. Technological or Performance factors considered in the recycling process.

The literature review found that the time of processing scrap is an essential factor that affects the recycling cost. Considering the time of processing a scrap in a particular activity is quite important. Nevertheless, the processing time depends on various performance factors like production rate losses, downtime losses, and setup time associated with each activity. Considering these performance factors in calculating actual processing time is quite essential.

There are two different factors- cycle time and actual processing time when it comes to processing time.

Cycle time (t_o) - The cycle time $\mathbf{t_0}$ for processing scrap in particular equipment is expressed as the sum of the actual value-adding time and handling time. Generally, it is considered in hours, and the handling time includes the loading and unloading time of a machine, and the cycle time does not consider any losses associated with equipment, whereas the actual processing time considers various losses associated with the equipment. Generally, downtime losses and production rate losses are the two major identified losses in the production process.

Downtime losses (q_s):

There will be some downtime t_s associated with the equipment in real life, and this downtime can be due to various reasons like equipment failure, tool failure, etc. The disturbances in the form of downtime t_s cause the actual processing time $\mathbf{t_p}$ greater than the cycle time $\mathbf{t_0}$ (Ståhl, et al., 2007).

The downtime losses can be calculated as

$$q_s = \frac{t_p - t_0}{t_p} = \frac{t_s}{t_p}$$ *Equation 9*

Production rate losses (q_p):

Sometimes, the cycle time t_0 has to be increased to t_{0r} to avoid unplanned downtime or meet the quality requirements or meet the demand. The associated losses with the increased cycle time can be considered as production rate losses (Ståhl, et al., 2007).

$$q_p = \frac{t_{or} - t_0}{t_{or}} = 1 - \frac{t_0}{t_{0r}}$$ *Equation 10*

Therefore, the actual processing time (t_p) can be expressed as the actual number of hours required for processing a ton of scrap in a particular piece of equipment. Unlike the cycle time, the actual processing time considers various losses associated with the equipment, and from above equations (9 & 10), actual processing time ($\mathbf{t_p}$) can be written as (Ståhl, et al., 2007).

$$t_p = \frac{t_0}{(1-q_P)(1-q_S)}$$ *Equation 11*

And the units for actual processing time is (Number of hours/ton)

Generally, in processing industries, it is obvious to process material in batches. When processing batches, in some cases, it may be necessary to take into account disturbances in the event of a changeover that gives downtime or requires extra time, which is considered as setup time.

Therefore,

Time for processing a batch (T_p):

The total time for processing a batch of size (X) through a processing step concerning production rate losses, downtime losses, and setup time T_{su} can be calculated as: (Ståhl, et al., 2007).

$$T_p = T_{su} + X.t_p \qquad \text{Equation 12}$$

Generally, the batch size can be varied from activity to activity due to losses associated with the material in each processing step. For example, 100 tonnes of scrap material are given as input to the disassembly stage. In the disassembly stage, 20 tonnes of the reusable material are separated from the input, and the remaining 80 tonnes of material is sent to the shredding and sorting stage. The batch size for disassembly activity is 100 tonnes, whereas the batch size for shredding and sorting activity is 80 tonnes. With the change in batch size, the processing time changes. We can say that it is crucial to consider various losses associated with the production process, actual processing time, setup time, and batch size while considering the costs associated with the recycling process.

3.4. Cost Drivers

A cost driver is a unit of activity that affects the change in the cost of an activity. For example, if a person operates a machine for ten hours at the cost of ten dollars per hour, the total cost that will be charged to the output of that time is one hundred dollars. The more labour hours used, the higher the cost. As mentioned in section **(3.1)**, in each activity, the cost of resources used is taken into consideration, and an appropriate cost driver is chosen, and then these economic factors are coupled with the above-mentioned performance factors.

Before choosing the appropriate cost drivers, the resources mentioned in **Table 1** are categorized into seven groups – Materials, Processing Equipment, Personnel, Material Handling, Transportation, Storage Area, and Additional cost. In the following **Table 2**, the resources that fall under each group, appropriate cost driver for each group, and units for each group are mentioned in detail.

The aim of the developed model for recycling is to calculate the cost of recycling per ton. Accordingly, all the groups except processing equipment and personnel have a unit of cost per ton, while the processing equipment and personnel have units as cost per hour. In section **(3.2),** we have seen that the actual processing time is very crucial in calculating recycling costs. The cost of processing equipment and the cost of personnel per hour is multiplied with actual processing time, where units are the number of hours for processing a ton of scrap material. By this, we can get the equipment cost and personnel cost in terms of cost per ton.

The equations for calculating the costs associated with materials, processing equipment, personnel, material handling, transportation, storage, and additional costs and the equation for calculating the cost of recycling per ton are discussed in detail in the results chapter.

Table 2: *Cost drivers for resources accountability in Recycling.*

Group	**Resources**	**Cost Driver**	**Units**
Materials	Scrap Material. Virgin Material. APR. Conversion Costs (associated with scrap material). Disposal cost (associated with waste).	Number of tonnes.	Cost / ton.
Processing Equipment	Processing equipment involved in all the activities.	Number of hours (both idle and operating).	Cost / hour.
Personnel	personnel involved in various activities, material handling, transportation.	Number of hours.	Cost / hour.

Material Handling	Material handling equipment In between all the activities and in between storage and various activities.	Number of tonnes handled in a year.	Cost / ton.
Transportation	Transporting equipment involved in various activities.	Number of tonnes handled in a year.	Cost / ton.
Storage	Storage area.	Number of hours (avg. storage time) and number of square meters of storage area.	Cost / ton.
Additional costs	Quality assurance Health and Safety Any activity-specific indirect costs.	Annual cost.	Cost / ton.

4. Developing a cost model for remanufacturing

Just like chapter 3, this chapter explains various activities and their associated costs involved in the remanufacturing process, various technological or performance factors considered in remanufacturing process. It explains appropriate cost drivers chosen for various resource groups.

4.1. Preface

Remanufacturing can be stated as "the rebuilding of a product to specifications of the original manufactured product using a combination of reused, repaired, and new parts" (Boagey, 2016). The cost model for remanufacturing is built in the same way as the cost model for recycling. In this model also, all the major activities involved in remanufacturing are identified, and appropriate cost drivers are chosen. Then the cost of resources involved in every activity is coupled with performance factors. In this model, only the activities in the remanufacturing facility are taken into consideration, and this model helps in calculating the cost of remanufacturing per product.

Based on the literature review, we found **eight** major activities involved in remanufacturing process. They are **disassembly, cleaning, inspection 1, machining and material addition, inspection 2, assembly, functional testing, and painting**. For building an economic model, all these activities are categorized into three stages. In **Stage 1**, disassembly is included. In **Stage 2**, cleaning, inspection 1, machining and material addition, and inspection two are included, and **Stage 3** includes assembly, functional testing, and painting are included. In section **4.2**, all these activities and their associated costs are explained in detail.

Similarly, production rate losses, downtime losses, quality losses, setup-time, cycle time, and actual processing time are the considered technological factors explained in detail in section **4.3,** and Section **4.4** explains the appropriate cost drivers and units chosen for various resource groups.

4.2. Major activities in remanufacturing and their associated costs

Generally, in standard business systems, the products will reach the distributors from the manufacturers and then from distributors to customers. However, in the remanufacturing system, the used products (also called cores) will reach the distributors from customers. Then the distributors will inspect the product, and if the product meets specific requirements and specifications, the distributors buy the product from the customers. Later these products are shipped to the warehouse or storage area of the remanufacturing facility.

Just like recycling, the processing time of a product or a part in a specific activity plays an essential role in calculating the cost of remanufacturing. Based on the complexity of the product, the product can be disassembled either parallelly or sequentially to maintain the processing time close to other activities, which helps in achieving higher production line efficiency.

Considering,

- K_M = cost of the old product (core) brought from the customer.
- K_{old} = Average cost of the old product (core) brought from the customer.
- A V8 engine is an example of a product for a better understanding of the concept.

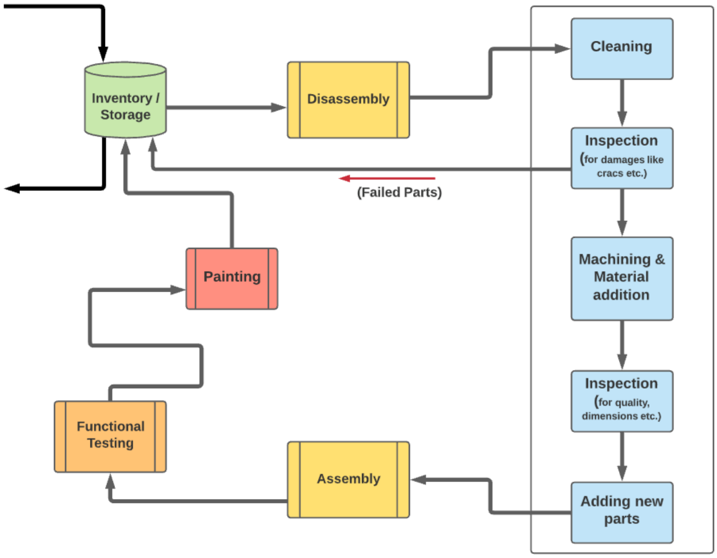


Figure 22: *Flow of products in Remanufacturing process.*

As mentioned in the **above** section, all the major activities involved in remanufacturing are categorized into three stages –

Stage 1 (K_1):

Disassembly ($K_{Disassembly}$): Remanufacturing process starts with this activity. The core or the product (V8 engine) from the warehouse is shipped to a disassembly station. In this station, the product is fixed inappropriate fixtures and then disassembled with the help of power tools or any product-specific tools. After disassembly, various parts of the product are separated and sent to **Stage 2** for further processing.

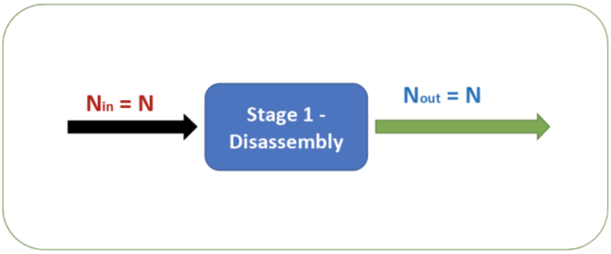


Figure 23: *Flow of resources in remanufacturing stage 1*

Major Resources-

- During the disassembly process, the product has to be on hold with appropriate fixtures, and the product has to be disassembled with some tools like spanners, for example. The costs associated with these fixtures and tools have to be taken into account, and these costs are being considered under additional process requirements (APR), which falls in the indirect cost's category because the tools for dismantling and fixtures are mandatory resources. However, they neither add any value to the product nor generates revenue.
- The personnel involved in disassembly activity are another primary resource that has to be considered since many disassembly activities are manually performed. The costs associated with personnel have to be considered.
- Disassembly is the starting activity in the remanufacturing process, which means processing a used product starts from here. The average cost of the used product (K_{old}) should be considered in this activity. The reason for considering the average cost of an old product instead of regular cost is discussed in detail in section **5.2.4.**

Therefore, the major resources involved in disassembly activity are used products, personnel, and additional process requirements.

The cost for disassembly ($K_{Disassembly}$) activity can be calculated as

$K_{Disassembly} = K_{Old} + K_{Personnel} + K_{APR}$ *Equation 13*

And the total cost associated with stage 1 (K_1) can be calculated as

$K_1 = K_{Disassembly}$ *Equation 14*

Stage 2 (K_2):

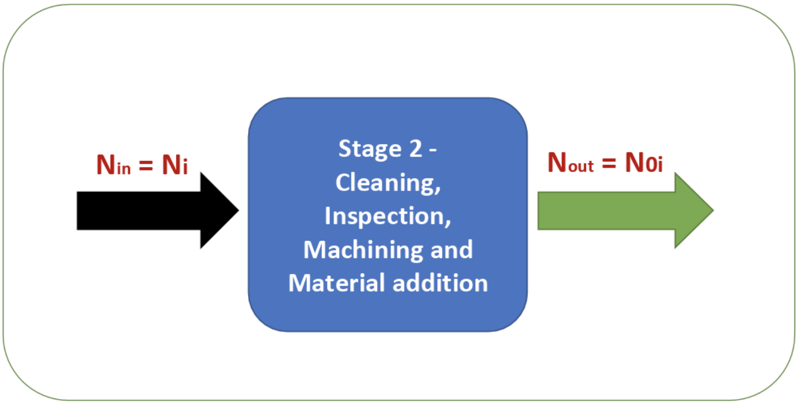


Figure 24: *Flow of resources in remanufacturing stage 2.*

1. **Cleaning ($K_{Cleaning}$):**

From **Stage 1**, the parts from the dismantled product will enter into the cleaning process. Generally, the parts from the used product are contaminated with various kinds of oils, grease, rust, paint, carbon deposits, and other foreign particles. So before sending the parts for inspection, in this activity, all the parts are thoroughly cleaned to make them free from contaminants like grease, lubricating oil, etc. Then from this activity, the cleaned parts are sent for inspection, which will be done in the following activity **- Inspection 1**.

Based on the type of product, an appropriate cleaning process is selected. Organic solvent cleaning technology, Jet cleaning technology, Thermal cleaning technology, Ultrasonic cleaning technology, and Electrolytic cleaning technology are the most common cleaning technologies used in remanufacturing process. In these cleaning technologies, various cleaning mediums like an organic solvent, detergent, acid solution, alkali solution, various solid particles are used for making the parts free from contaminants.

Major Resources-

- The suitable equipment for the selected cleaning process is one of the significant resources to be considered. Based on the selected cleaning process, a suitable cleaning medium has to be selected. The cleaning medium is another critical resource to be considered, and it is considered under additional process requirements (APR). However, in this case, the APR falls under the direct cost category since it adds some value to the parts.
- In this activity, personnel are required to monitor the process and for handling the equipment. The personnel associated with the cleaning activity is another essential resource to be considered.

Therefore, the major resources involved in cleaning activity are cleaning equipment, personnel, and additional process requirements.

The cost for processing a part in cleaning ($K_{Cleaning}$) activity can be calculated as

$$K_{Cleaning} = K_{Equipment} + K_{Personnel} + K_{APR} \qquad \textit{Equation 15}$$

2. **Inspection 1 ($K_{Inspection1}$):**

   All the cleaned parts are inspected for damages, wear, and any other surface defect in this activity. Generally, the type of inspection depends on the type of the part. For example, a crankshaft is inspected by personnel with a naked eye to detect any surface damages, but a fuel injector is inspected by using internal bores to detect the quality of the internal surface of the fuel injector. Based on the type of part and degree of its complexity appropriate inspection technique is chosen.

In this inspection, if the parts meet certain specifications and requirements, then they are sent to the next activity. Otherwise, the parts will be rejected and considered as scrap and the number of parts that met the requirement will vary from batch to batch since it depends on the condition of the purchased core.

Major resources-

- In this inspection activity, depending on the type of the part, sometimes only the personnel will perform the task, and sometimes the personnel aided with equipment will perform the task. The cost associated with both the equipment and personnel has to be taken into account.

The major resources involved in this activity are inspection equipment and personnel.

The cost for processing a part in inspection 1 ($K_{Inspection1}$) activity can be calculated as

$$K_{Inspection1} = K_{Equipment} + K_{Personnel.} \qquad \textit{Equation 16}$$

3. Machining and Material addition (K_{MM}):

All the parts that are qualified in **Inspection 1** will enter this activity. Based on the identified issues and the quality of the part, an appropriate technique is chosen. For instance, if there are cracks on the exterior of the crankshaft, then the surface is machined first. Then to compensate for the material loss due to machining, new material is added through the fusion welding process so that the dimensional tolerance is maintained.

Generally, defects like cracks, nicks and burrs, and other inclusions result from interaction processes such as friction, impact loads, elevated and high temperatures, and corrosion, and machining processes can remove these as turning, milling, drilling, grinding, etc. Through material added substance cycles like welding, powder covering, and laser cladding, aside from "cavities," can be re-established to its planned shape and gross dimension. The appropriate method is chosen based on the requirements and nature of the surface. In some cases, after this machining and material addition process, an appropriate conditioning process, such as heat treatment, is chosen to achieve the desired properties and to remove unwanted residual stresses. After all these processes, all the parts are transferred to **Inspection 2** for final inspection of parts.

Major Resources-

- In this activity, various kinds of advanced equipment like CNC machines, welding equipment, vapor deposition equipment, etc., are required for material removal and addition processes. The cost of all this equipment has to be taken into consideration.
- In material removal operation, various tools like turning tools, milling tools, boring tools, etc., have to be considered as one of the major resources.
- In material addition or deposition technique, a material of appropriate grade must be added to the part. The cost of the material has to be considered.
- In some material addition processes, inert gases are used for shielding purposes and welding purposes, and some tools like welding electrodes are also used. All these are considered under additional process requirements, and these costs fall under the direct cost category since they play a crucial role in the value addition process.
- And for monitoring the processes and handling the material removal and addition equipment, personnel are required. Personnel associated with the whole activity has to be considered.
- Therefore, the major resources involved in this activity are equipment (for machining and material adding), personnel, cutting tools, new material, and additional process requirements.

  The cost for processing a part in machining and material addition (K_{MM}) activity can be calculated as

$$K_{MM} = K_{Material} + K_{Tool} + K_{Equipment} + K_{Personnel} + K_{APR} \qquad \textit{Equation 17}$$

4. Inspection 2 ($K_{inspection2}$):

From the **Machining and Material addition** activity, the processed parts enter this activity. In this activity, the parts are inspected to check the dimensional accuracy, surface finish and ensure that the part meets the quality requirements. Generally, this inspection is done by using high precision equipment to ensure the dimensional accuracy in microns. In some cases, the costs associated with this activity can also be considered as quality assurance costs.

If any parts do not meet the quality requirements, they are sent back to the machining and material addition activity for reprocessing. In this way, the quality of the parts is maintained.

Major resources-

- Various equipment like 3D Optical Profilometry, surface roughness gauges, etc., are used to inspect the equipment. The cost of this equipment has to be taken into consideration.
- Skilled personnel is required to operate the equipment and examine the results. The personnel involved in this activity has to be taken into consideration.
- The major resources involved in this activity are inspection equipment and personnel.

The cost for processing a part in inspection 2 ($K_{Inspection2}$) activity can be calculated as

$$K_{Inspection2} = K_{Equipment} + K_{Personnel.} \qquad \text{Equation 18}$$

Therefore, the cost for processing a part in stage 2 (K_2) can be calculated as

$$\mathbf{K_2 = K_{Cleaning} + K_{Inspection1} + K_{MM} + K_{Inspection2.}}$$

With **the above equation,** the total cost for processing a single part of a specific type in **Stage 2** can be calculated, but in the product, few parts are in multiple numbers; for example, a V8 engine contains eight pistons or 16 valves, etc. We have to consider the cost of the total number of parts used in a product since we are calculating the cost of remanufacturing a product (core). But In this stage, after **Inspection 1**, few parts are rejected because

the parts haven't met the desired requirements and specifications and the number of parts rejected varies from batch to batch. These rejected parts should be replaced with either new parts or used parts (should pass inspection one and inspection 2) in order to assemble the product. The cost of these new or used parts used in the product has to be considered.
Considering,

- N = number of parts of a specific type used in a product
- N_{Reman} = Number of remanufactured parts used in a product.
- $N_{New/Used}$ = Number of used or new parts used in a product.
  ($N = N_{Reman} + N_{New/Used}$)

- ($K_{New/used}$) = Cost of new or used part.

For example, as mentioned, a V8 engine contains eight pistons. Eight pistons are passed through cleaning and inspection 1 activity. But out of 8 pistons, only seven pistons are qualified inspection 1 and one piston got rejected. These qualified seven pistons are further processed in the following machining and material addition activity and these seven pistons qualified inspection 2 activity. Now, to assemble the product, we need eight pistons. So, the rejected one piston has to be replaced with either used or a new piston.

Therefore, N = 8, N_{Reman} = 7 and $N_{New/used}$ = 1.
So, while calculating the cost of a product, the cost of (7+1) pistons have to be considered.

Therefore,

$$K_2 = ((N)\,(K_{Cleaning} + K_{Inspection1}) + ((N_{Reman})\,(K_{MM} + K_{Inspection2})) + ((N_{New/Used}) + (K_{New/used})) \qquad \textit{Equation 19}$$

With this equation, the total cost for a specific part (either pistons or valves) can be calculated. But a product (core) contains Z number of various parts (For example, an engine contains a cylinder, cylinder head, camshaft, crankshaft, timing belt……Z.), and all the parts have to be processed in all the activities in **Stage 2**. So, the costs associated with every specific type of part have to be considered since we are calculating the cost of remanufacturing per product.

Therefore, the cost for processing a product in stage 2 can be calculated as

$$\sum_{i=1}^{Z} K_2$$

From this stage, all the parts will enter into stage 3. In this stage, all the parts are assembled into a product and functionally tested.

Stage 3 (K_3):

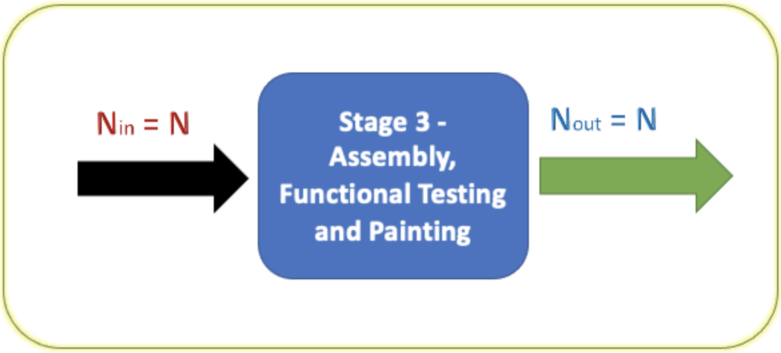


Figure 25: *Flow of resources in remanufacturing stage 3.*

1. Assembly ($K_{Assembly}$):

Various kinds of parts involved in the product are gathered. In this activity, these parts are assembled into a product. Like disassembly, assembling a product also plays a crucial role in calculating the cost of assembly. To keep the assembly time close to the processing time of other stations, the product is parallelly assembled as various modules. Then all the modules are assembled into a final product. After assembly, the product is sent to the functional testing centre.

Major Resources-

- Like disassembly, the product has to be on hold with appropriate fixtures during the assembly process. The product has to be assembled with some tools like spanners, power drills, etc. The costs associated with these fixtures and tools have to be taken into account, and these costs are being considered under additional process requirements, which falls in the indirect costs category because the tools for assembling, and the fixtures are the mandatory resources. However, they neither add any value to the product nor generates revenue.
- The personnel involved in assembly activity is another major resource that must be considered since most of the assembly activities are manually performed. The costs associated with personnel has to be considered.

Therefore, the major resources involved in assembly activity are personnel and additional process requirements.

The cost for processing a product in assembly ($K_{assembly}$) activity can be calculated as

$$K_{assembly} = K_{Personnel} + K_{APR} \qquad \textit{Equation 20}$$

2. **Functional testing ($K_{Func.Testing}$):**

In this activity, the assembled product is subjected to all the tests that a new product has been through to ensure that the remanufactured product is suitable for real-life operations. For example, a remanufactured engine is tested using a whole floor-mounted engine test rig with modular instrumentation and control systems. With this kind of testing, various kinds of tests like torque-speed performance tests under steady-state and transient state, volumetric and mass emission tests, fuel consumption tests, etc., are performed to ensure that the product is ready for real-life application. After the product qualifying, this test, a new product number with a covered warranty is issued for the product.

Major resources:

- The appropriate testing rigs for testing the product and serial number generators are the primary equipment that has to be considered in this activity.
- Skilled personnel is required for handling the test rigs and validating the data. The personnel associated with this activity has to be considered as another critical resource.
- For example, while testing the engine, it has to be filled with supplements like fuel, coolants, lubricating oil, etc. All these kinds of supplements are involved in testing various kinds of products. This kind of supplement can be considered additional process requirements that fall under the indirect cost category.

Therefore, the major resources involved in this activity are testing equipment (test rigs), personnel, and additional process requirements.

The cost for processing a product in functional testing ($K_{Func.\ Testing}$) activity can be calculated as

$$K_{Func.\ Testing} = K_{Equipment} + K_{Personnel} + K_{APR} \qquad \textit{Equation 21}$$

3. **Painting ($K_{painting}$):**

Generally, in this activity, the parts or the products are applied with new paint or surface coating or protective layers to protect them from the external environment. Along with these painting operations, sometimes surface finishing operations can also be performed in this activity. Painting activity is optional and can also be placed at any position in this stage (i.e., either before assembly or after assembly, or after functional testing) based on the type of product. For example, Mini Sport is one of the world’s leading premier suppliers of remanufactured A series A+ engine and components for Mini, and they paint the cylinder block before assembling.

Major Resources-

- The surface coating equipment or the painting equipment like robotic arms are the major resources to be considered in this activity.
- Generally, in this activity, personnel are required to make up the products in the paint room, feed the surface coating equipment, etc. The personnel involved in this activity have to be considered.
- The surface coating equipment requires additional requirements like coolants, cleaning the equipment before changing to another colour or other type of protective coating, etc. All these additional requirements are considered under additional costs, which fall under indirect costs.

Therefore, the major resources involved in this activity are equipment (robotic arms), personnel, paint, and additional process requirements.

The cost for processing a product in painting ($K_{Painting}$) activity can be calculated as

$$K_{painting} = K_{paint/coating} + K_{Equipment} + K_{Personnel} + K_{APR} \qquad \textit{Equation 22}$$

Therefore, the cost for processing a product in **Stage 3** can be calculated as

$$K_3 = K_{Assembly} + K_{Func.\ Testing} + K_{painting} \qquad \textit{Equation 23}$$

As mentioned in section **(4.1)**, this model considers only the activities taking place within the remanufacturing facility. The transportation costs associated with the transport of cores to the remanufacturing facility and from the remanufacturing facility are being avoided. But for transporting the cores and the parts between various activities and between activities and storage area within the remanufacturing facility, a material handling system is required. Calculating the material handling cost ($K_{Material\ Handling}$) for every activity making the model more complex by demanding more data. Instead of calculating these costs for every activity, we are calculating them for the whole remanufacturing process, as explained in section **(5.1.5).**

Similarly, none of the stages considered storage cost ($K_{Storage}$). However, it is one of the essential indirect costs to be considered. Initially, the products are taken from the storage or warehouse and then sent to processing activities.

After final testing and painting, the products are sent back to the warehouse either for storing or preparing to deliver to the customer. Also, in the warehouse, the rejected parts and spare parts will be stored. Considering the cost of storage is quite important, and the considerations in calculating the storage cost are explained in detail in section **(5.2.7).**

Similar to recycling process, there are many costs associated with various activities in the remanufacturing process. For simplification, all the costs are classified into direct and indirect costs, as shown **in Table 3.** All the direct and indirect costs mentioned **below** table are the findings from the literature review, but along with these costs, there might be chances of the presence of some hidden costs in every activity like local buffers, local storage equipment, safety equipment, etc. These hidden costs are considered additional costs ($K_{\text{Additional}}$) and calculating them for every activity makes the equation more complex by demanding more data. In this case considering them for the whole remanufacturing process is the most optimal, as explained in detail in the section (5.2.8).

Therefore, the total cost for remanufacturing ($K_{\text{Remanufacturing}}$) a product can be calculated as

$$K_{Remanufacturing} = K_1 + \sum k_2 + k_3 + k_{material\ handling} + k_{storage} + K_{Additional}$$

Equation 24

Table 3: *Various costs associated with remanufacturing.*

Activity	Resources	Direct Costs	Indirect costs
Disassembly	Personnel. APR. Core. Material Handling.	Personnel. Core.	APR. Material Handling.
Cleaning	Equipment. Personnel. APR. Material Handling.	Equipment. Personnel. APR.	Material Handling.
Inspection 1	Equipment. Personnel. Material Handling.	Equipment Personnel	Material Handling.
Machining and Material addition	Material. Tools. Equipment. Personnel. APR. Material Handling.	Material. Tools. Equipment. Personnel. APR.	Material Handling.
Inspection 2	Equipment. Personnel. Material Handling.	Equipment. Personnel.	Material Handling.
Assembly	APR. Personnel.	Personnel.	APR. Material Handling.

	Material Handling.		
Functional Testing	Equipment. Personnel. APR. Material Handling.	Equipment. Personnel.	APR. Material Handling.
Painting	Paint/coating. Equipment. Personnel. APR. Material Handling.	Paint/Coating. Equipment. Personnel.	APR. Material Handling.

4.3. Technological or Performance factors considered in Remanufacturing.

From the literature review, it was found that the time of processing a product, or a part is an essential factor that affects the cost of remanufacturing. Considering the time of processing a product or a part in a particular activity is quite important. As explained in section **(3.3),** the processing time is mainly dependent on various performance factors like production rate losses, downtime losses, and setup time associated with each activity. Considering these performance factors in calculating actual processing time is crucial.

The same performance factors mentioned in section **(3.3)** will be using in the remanufacturing process but how those factors are being considered varies in remanufacturing process.

Cycle time (t_o) - The cycle time **t_0** for **processing, either a product or a part** in particular equipment is expressed as the sum of the actual value-adding time and handling time. Here also, the cycle time will be considered in hours and the handling time includes the loading and unloading time of a machine. The cycle time does not consider any losses associated with equipment. In contrast, the actual processing time considers various losses associated with the equipment. Generally, downtime losses and production rate losses are the two major identified losses in the production process.

The downtime losses (q_s) and the production rate losses (q_p) remain the same in both the recycling and remanufacturing process, and for remanufacturing process, they can be calculated by using equations **(9 & 10)**
In remanufacturing, the actual processing time can be expressed as an actual number of hours required for processing either a product or a part of particular equipment. Therefore, t_p can be calculated as (Ståhl, et al., 2007)

$$t_p = \frac{t_0}{(1-q_P)(1-q_S)} \qquad \textit{Equation 25}$$

Generally, it is obvious to switch from part A to part B and from one product to another product and from one batch to another in remanufacturing industries. During the changeover, in some cases, it may be necessary to take into account disturbances in the event of a changeover that gives downtime or requires extra time, which is considered as setup time.

Therefore,
The total time for processing a batch (T_p) can be expresses as
The total time for processing a batch of size (x) through a processing step concerning production rate losses, downtime losses, and setup time T_{su} can be calculated as: (Ståhl, et al., 2007)

$$T_p = T_{su} + x.t_p \qquad \textit{Equation 26}$$

In remanufacturing, the batch size can be varied from activity to activity, product to product, and also from specific part type to another. For example, considering 10 V8 engines for remanufacturing. The batch size for **Stage 1** and **Stage 3** is 10 since we are considering products in these two stages. Now every engine contains 8 pistons. So, for 10 engines, there will be 80

pistons, and these 80 pistons have to pass through **Stage 2**. 80 is the batch size for stage 2 for pistons.
But along with pistons, all the other components in an engine have to be processed. Let us consider the crankshaft, and every engine contains one crankshaft that means 10 engines contain 10 crankshafts. So, the batch size is 10 for stage 2 for the crankshaft. This how batch size varies from one activity to another activity and from one specific part to another.

So, while calculating the remanufacturing cost, it is important to consider the total time for processing a batch since it considers actual processing time, batch size, and the associated setup time.

4.4. Cost Drivers

Similar to recycling, in remanufacturing process, the cost of resources used in each activity is taken into consideration, and an appropriate cost driver is chosen, and then these economic factors are coupled with the above-mentioned performance factors.

Just like in section **(3.4)**, before choosing the appropriate cost drivers, the resources mentioned in **Table 3** are categorized into 8 groups – Materials, Tools, Equipment, Personnel, Additional process requirements, Material Handling, Storage Area, and Additional cost. In the following **Table 4** the resources that fall under each group, appropriate cost driver for each group, and units for each group are mentioned in detail.

The developed model for remanufacturing aims to calculate the cost of remanufacturing per product. Accordingly, all the groups except processing equipment and personnel have a unit of cost per ton, while the processing equipment and personnel have units as cost per hour. In section **(4.3)**, we have seen that the actual processing time is very crucial in calculating remanufacturing cost. the cost of processing equipment and the cost of personnel per hour is multiplied with actual processing time associated with various activities. By this, we can get the equipment cost and personnel cost in terms of cost per product.

The equations for calculating the costs associated with materials, tools, equipment, personnel, material handling, additional process requirements, storage, and additional costs and the equation for calculating cost of remanufacturing per product are discussed in detail in the **Results** chapter.

Table 4: *Cost drivers for Remanufacturing*

Group	Resources	Cost Driver	Units
Materials	Used product. Material added in machining and material addition activity. Paint/ Coating.	Number of products.	Cost / Product.
Tools	Machining tools in machining and material addition activity.	Batch size.	Cost / Product.
Equipment	Equipment involved in all the activities.	Number of hours (both idle and operating).	Cost / hour.
Personnel	personnel involved in all the activities and associated with material handling equipment.	Number of hours.	Cost / hour.
Additional Process Requirements	All the activities in which APR is involved.	Batch size.	Cost / Product.

Material Handling	Material handling equipment In between all the activities and in between storage and various activities.	Number of batches.	Cost / Product.
Storage	Storage area.	Number of hours (avg. storage time) and number of square meters of storage area.	Cost / Product.
Additional costs	Any activity-specific indirect costs.	Annual cost.	Cost / Product.

5. Results

*This chapter presents cost equations for calculating the costs associated with various resource groups mentioned in section **3.4 and 4.4** and also explains the cost equations for calculating the cost of recycling per ton and the cost of remanufacturing per product.*

5.1. Cost equations associated with recycling process.

As mentioned in section **3.4**, the recycling process contains seven resource groups- processing equipment, personnel, materials, material handling, transportation, storage, and additional costs. The costs associated with each resource group play a crucial role in the total cost of recycling. The cost associated with each resource group can be calculated as explained below.

5.1.1. Processing equipment cost ($K_{Equipment}$)

As shown in **Table 2**, initially, the cost of processing equipment will be calculated in terms of cost per hour. However, we need the cost of processing equipment in terms of cost per ton since we are calculating the cost of recycling per ton. The equipment hourly cost is multiplied by **the total time for processing a batch in a particular activity and then divided with the output of that activity**. the cost of processing equipment per ton will be achieved.

The equipment hourly cost can be calculated by dividing the equipment's yearly cost by the total number of planned production hours in a year (T_{plan}).

The equipment's yearly cost can be calculated using the annuity method, which results in a constant annual cost, distributed on the entire duration of **ny** number of years that the equipment is expected to be used. K_0 denotes the basic investment in the equipment, and the interest rate is denoted by **P**. The annual cost of equipment '**a**' can be calculated as (Ståhl, et al., 2007)

$$a = K_0 \,.\, \frac{p\,.\,(1+p)^{ny}}{(1+p)^{ny}-1}$$ *Equation 27*

The annotation factor **a_f** =

$$a = .\ \frac{a}{K_0}$$ *Equation 28*

Along with the annual cost **a**, the yearly equipment cost also includes the cost of premises associated with the machine ($A.K_{Area}$), ongoing maintenance costs (K_{MH}), renovation costs (K_{ren}), and energy costs (K_{energy}).

As mentioned, the equipment hourly cost (K_C) can be calculated by dividing the equipment yearly cost by total planned production hours (**T_{plan}**) in a financial year. For example, a recycling plant runs for 16 hours a day (2 shifts), and the plant runs five days a week, which means that the plant runs for 80 hours a week. In a year, there are 52 weeks; hence the T_{plan} for that recycling plant will be 4160 hours.

For calculating the equipment cost more precisely, the equipment hourly cost is classified into two types. They are Equipment hourly cost when running (**K_{CP}**) and equipment hourly cost at a standstill (**K_{Cs}**). The basic difference between them is in K_{Cs}, maintenance cost and the energy cost will be omitted since the equipment is at a standstill.

The equipment's hourly cost when running (K_{CP}) can be calculated as (Ståhl, et al., 2007)

$$K_{CP} = \frac{a_f \cdot K_0(1 + K_{0ren} \cdot N_{ren}) + A.K_{Area} + \ K_{MH} + \ K_{energy}}{T_{Plan}}$$

Equation 29

The equipment's hourly cost during standstill (K_{CS}) can be calculated as (Ståhl, et al., 2007)

$$\boldsymbol{K_{CS} = \frac{a_f \cdot K_0(1+K_0 \cdot N_{ren})+A.K_{Area}}{T_{Plan}}} \qquad \textit{Equation 30}$$

Where:
A = The area tied to the equipment.
K_{Area} = The cost of area per square meter per year.
K_{MH} = The yearly maintenance cost.
K_{energy} = The yearly energy costs associated with equipment.

And K_{ren} is the present value of renovation cost which is expressed as a percentage of basic investment K_0. N_{ren} represents the number of renovations required throughout the planned period of use. The number of renovations can be calculated as the integer part of trunc (x) of the ratio between the total number of shifts and renovation interval (number of shifts between each renovation) (Windmark, et al., 2012)

$$N_{ren} = trunc\left(\frac{n\,.\frac{T_{plan}}{h_{year}}}{n_{syren}}\right) \qquad \textit{Equation 31}$$

From the above 29 & 30 equations, the equipment cost per hour while processing and at a standstill can be obtained. To express the equipment's cost in terms of cost per ton, it should be multiplied with the total time for processing a batch in a particular activity and then divide with an output of that activity.

We know that the total time for processing a batch includes setup time, downtime losses, production rate losses, and cycle time. Generally, the downtime and setup time leads the equipment to be at a standstill. While calculating the equipment cost at a standstill, only downtime and setup time are considered. On the other hand, when the equipment runs, the actual processing time with production rate losses is considered. Because the production rate losses occur due to change in cycle time, and it doesn't lead the equipment to a standstill.

Therefore,

The equipment cost per ton during processing can be written as:

$$\frac{K_{CP}}{x_{out}}\left(\frac{t_0.\ x_{in}}{(1-q_p)}\right) \qquad \textit{Equation 32}$$

The equipment cost per ton during standstill can be written as:

$$\frac{K_{CS}}{x_{out}}\left(\frac{t_0.\ x_{in}}{(1-q_p)}\ .\ \frac{q_s}{(1-q_s)}+\ T_{su}\right) \qquad \textit{Equation 33}$$

As we know, the batch size plays a crucial role in determining the total time for processing a batch. The batch size can vary from one activity to another due to various kinds of material losses in each activity, as mentioned in section **3.3**. It is important to consider the respective batch size in each activity. In the above 32 and 33 equations, a term called $\mathbf{x_{in}}$ is considered, which represents the total number of tons of material entered into a particular activity and can also be called the batch size of a particular activity. Similarly, to get the cost of processing equipment per ton, the equipment hourly cost is multiplied by the total time for processing a batch in a particular activity ($\mathbf{x_{in}}$) and then divided with the output of that activity. In equations above 32 and 33, a term called $\mathbf{x_{out}}$ is considered, representing the output of a particular activity in terms of a number of tons. Therefore, (X_{in} - X_{out}) of a particular activity can be considered as a material loss in that activity.

Therefore,

$$K_{Equipment} = \frac{K_{CP}}{x_{out}}\left(\frac{t_0.\ x_{in}}{\left(1-q_p\right)}\right)+\frac{K_{CS}}{x_{out}}\left(\frac{t_0.\ x_{in}}{\left(1-q_p\right)}\ .\ \frac{q_s}{(1-q_s)}+\ T_{su}\right)$$

Equation 34

5.1.2. Personnel cost ($K_{Personnel}$)

Like processing equipment cost, the personnel cost is initially taken in terms of cost per hour. But we need the personnel cost per ton since we are calculating the cost of recycling per ton. The personnel hourly cost is multiplied by the total time for processing a batch in a particular activity and then divided with the output of that activity (x_{out}).

As we know that, the total processing time of a batch includes the cycle time, downtime losses, production rate losses, and setup time. And during the total processing time, the presence of personal at the equipment is a must since the personnel will be either monitoring the process/handling the equipment to resolve the encountered issues. When calculating the cost of personnel per ton, we are considering the total processing time of a batch.

The personnel cost per ton can be calculated as

$$K_{Personnel} = \frac{K_D \cdot N_{OP}}{x_{out}} \left(\frac{t_0 \cdot x_{in}}{(1-q_p) \cdot (1-q_s)} + T_{su} \right) \qquad \textit{Equation 35}$$

Where:

$K_{D.}$ = cost of an operator per hour.

$N_{op.}$ = Number of operators.

However, in **Activity 1** (Collection and storage), no value-adding processes and processing stations are involved. There won't be any cycle times, downtime losses, production rate losses, and setup times. But in this activity, during the whole planned production time (T_{plan}), personnel are required to handle and organize the materials in the storage area.

For activity 1, the personnel costs can be calculated as

$$\frac{\boldsymbol{K_D . N_{OP}}}{\boldsymbol{x_n}} (\boldsymbol{T_{Plan}}) \qquad \textit{Equation 36}$$

In the above equation 36, we are multiplying the operators' hourly cost with T_{plan}, which results in operators' yearly cost. Since we are calculating the cost of recycling per ton, the yearly cost of operators is distributed over the yearly output of a recycling facility (x_n) which is the total number of tonnes of material formed by a recycling facility into bars, blocks, etc. in planned production time in a year.

5.1.3. Equipment and personnel costs for each activity

From the above equations (34, 35), we can see that the total number of tons of material entering a particular activity (x_{in}) and the total number of tons of material exiting that activity (x_{out}) plays a crucial role in determining equipment and personnel costs associated with in the activity. To understand it in a more detailed way, the following assumptions are taken into consideration.

As shown in Figure 18

- x is the total number of tonnes of scrap collected from the warehouse for processing, and it can also be called a batch of scrap material. Therefore, x is the x_{in} for disassembly activity.
- This x tonnes of scrap material consists of x_1 tonnes of desired recyclable material (for example, steel), x_2 tonnes of reusable material, and x_3 tonnes of unwanted materials (like glass, plastics, composites, and other metals).
- Therefore, $x = x_1 + x_2 + x_3$.
- x_4 is the total number of tonnes of waste generated during pre-treatment and processing activity.
- x_5 is the total number of tonnes of virgin material added during pre-treatment, and processing activity
- x_6 is the total number of tonnes of material formed into bars, blocks, etc. This is also called the output of the recycling plant obtained by processing x tonnes of scrap material.
- x_7 is the total number of tonnes of non-recyclable material, processed hazardous waste, and any other additional compounds generated

while processing various kinds of waste in the waste management centre.
- x_n is the yearly output of a recycling facility: the total number of tonnes of material formed by a recycling facility into bars, blocks, etc., in planned production time in a year.

As described in the collection and storing **Activity 1**, If the collected scrap is a mixed scrap or complex product, then x_1, x_2, x_3 have to be considered. Suppose the collected scrap is a high-value scrap from machining operations in the manufacturing industry. In that case, $x_2= x_3=0$ since the scrap from the machining process is already sorted. For this type of scrap, disassembly activity and the shredding process can be avoided since the scrap generated from machining operations will be in the form of chips. It requires neither disassembly nor shredding.

1. Disassembly activity –

In the recycling facility, the recycling process starts with disassembly. As shown in Figure 18**,** a batch of scrap material of size x is given as input to disassembly. All the reusable material (x_2) is separated in this stage, and all other materials (x_1 + x_3) are sent to the shredding station.

for Disassembly activity**,**

- $x_{in} = x$
- $x_{out} = (x_1 + x_3)$

Therefore,

The equipment cost per ton during processing can be calculated as:

$$\boldsymbol{\frac{K_{CP}}{(x_1+x_3)}\left(\frac{t_0 .\ x}{(1-q_p)}\right)} \qquad \textit{Equation 37}$$

The equipment cost per ton during standstill can be calculated as:

$$\boldsymbol{\frac{K_{CS}}{(x_1+x_3)}\left(\frac{t_0 .\ x}{(1-q_p)} \cdot \frac{q_s}{(1-q_s)} + T_{su}\right)} \qquad \textit{Equation 38}$$

The personnel cost per ton can be calculated as:

$$\frac{K_D.\ N_{OP}}{(x_1+x_3)}\left(\frac{t_0.\ x}{(1-q_p).\ (1-q_s)} + T_{su}\right) \qquad \textit{Equation 39}$$

2. Shredding and sorting activity

The output of the disassembly activity will be the input to the shredding and sorting activity. All the unwanted materials x_3 (like composites, plastics, and other non-desired metals) are separated in this activity. Only the desired recyclable material (x_1) is sent to the pre-treatment and processing activity.

For the Shredding and sorting activity,

- $x_{in} = (x_1 + x_3)$
- $x_{out} = (x_1)$

Therefore,
The equipment cost per ton during processing can be calculated as:

$$\frac{K_{CP}}{(x_1)}\left(\frac{t_0.\ (x_1+x_3)}{(1-q_p)}\right) \qquad \textit{Equation 40}$$

The equipment cost per ton during standstill can be calculated as:

$$\frac{K_{CS}}{(x_1)}\left(\frac{t_0.\ (x_1+x_3)}{(1-q_p)}\ .\ \frac{q_s}{(1-q_s)} + T_{su}\right) \qquad \textit{Equation 41}$$

The personnel cost per ton can be calculated as:

$$\frac{K_D.\ N_{OP}}{(x_1)}\left(\frac{t_0.\ (x_1+x_3)}{(1-q_p).\ (1-q_s)} + T_{su}\right) \qquad \textit{Equation 42}$$

3. Pre-treatment and processing activity –

All the desired recyclable scrap material (x_1) enters the pre-treatment and processing activity from the shredding and sorting activity. In this activity, the scrap material is either cleaned or chemically reacted with reagents and then melted in an appropriate furnace, and x_5 amount of virgin material is added to the molten scrap material to achieve the desired quality. Later the material is formed into bars, blocks which are represented as x_6. Also, during cleaning, melting, and forming, various kinds of wastes (slag, dust, sludge, etc.) are generated. This waste is considered x_4, which is collected and sent to the waste management activity. All the formed material (x_6) is sent to the warehouse or to the distributors from the pre-treatment and processing stage.

For pre-treatment and processing activity

- $x_{in} = (x_1)$
- $x_{out} = (x_6)$

$$x_6 = (\eta_{recycling} \,.x_1) + x_5$$

As mentioned in section 3.2.4, the pre-treatment stage is used for converting the scrap material into intermediate compounds in some recycling processes. There will be a substantial extent of material loss in the furnace due to various chemical reactions like oxidation, reduction, or other chemical reactions. This loss is being considered under recycling efficiency. Then based on the recycling efficiency, desired quality, and quality inspection results required amount of virgin material (x_5) is added to the molten scrap material.

Therefore,

The equipment cost per ton during processing can be calculated as:

$$\boldsymbol{\frac{K_{CP}}{(x_6)}\left(\frac{t_0 \cdot\ (x_1)}{(1-q_p)}\right)} \qquad \textit{Equation 43}$$

The equipment cost per ton during standstill can be calculated as:

$$\boldsymbol{\frac{K_{CS}}{(x_6)}\left(\frac{t_0 \cdot\ (x_1)}{(1-q_p)} \cdot \frac{q_s}{(1-q_s)} + T_{su}\right)} \qquad \textit{Equation 44}$$

The personnel cost per ton can be calculated as:

$$\boldsymbol{\frac{K_D \cdot\ N_{OP}}{(x_6)}\left(\frac{t_0 \cdot\ (x_1)}{(1-q_p) \cdot\ (1-q_s)} + T_{su}\right)} \qquad \textit{Equation 45}$$

4. **Waste Management activity** –

During the recycling process, various kinds of waste are generated in various stages, which must be treated before either disposing or transporting to the other recycling facilities. From storage, the waste generated in shredding and sorting activity (x_3) is collected and sorted. From the storage area, they are shipped to the waste management center. In this center, further sorting is done to separate the recyclable material from non-recyclable material. From here, all the recyclable material is transported to appropriate recycling facilities, and the non-recyclable materials are transported for disposal. Similarly, the waste generated in pre-treatment and processing activity (x_4) is collected and treated by using appropriate treatment methods and appropriate reagents to make the waste in-toxic and less harmful to the environment, as explained in section 3.2.5. Some kinds of waste, like Sludge, for example, is treated for separating the suspended metallic particles. Few materials can also be recovered from the waste generated in the recycling facility by this waste treatment activity.

For waste management activity

- $x_{in} = (x_3 + x_4)$

In the other activities, while calculating the equipment costs, the total cost for processing a batch in a particular activity was distributed over the output of that activity, but this is not the case for waste management activity. The total waste generated in shredding and sorting, pre-treatment, and processing activities is being processed in the waste management activity. The total cost of processing the waste has to be distributed over the output of the recycling plant (x_6), which is obtained by processing (x) tonnes of scrap material. Because in general, while calculating the manufacturing cost per product, the total cost of processing a batch and the total cost of input resources will be distributed over the output of the manufacturing plant to estimate the manufacturing cost of a single product. Similarly, the total cost of processing the waste is distributed over the output of the recycling plant.

Therefore,

- $x_{out} = (x_6)$

Therefore,
The equipment cost per ton during processing can be calculated as:

$$\frac{K_{CP}}{(x_6)}\left(\frac{t_0.\ (x_3)}{(1-q_p)}\right)+\frac{K_{CP}}{(x_6)}\left(\frac{t_0.\ (x_4)}{(1-q_p)}\right)$$

Equation 46

The equipment cost per ton during standstill can be calculated as:

$$\frac{K_{CS}}{(x_6)}\left(\frac{t_0.\ (x_3)}{(1-q_p)}\ .\ \frac{q_s}{(1-q_s)}+\ T_{su}\right)+\frac{K_{CS}}{(x_6)}\left(\frac{t_0.\ (x_4)}{(1-q_p)}\ .\ \frac{q_s}{(1-q_s)}+\ T_{su}\right)$$

Equation 47

Similarly, the personnel cost per ton can be calculated as:

$$\frac{K_D.\ N_{OP}}{(x_6)}\left(\frac{t_0.\ (x_3)}{(1-q_p).\ (1-q_s)}\ +\ T_{su}\right)+\frac{K_D.\ N_{OP}}{(x_6)}\left(\frac{t_0.\ (x_4)}{(1-q_p).\ (1-q_s)}\ +\ T_{su}\right)$$

Equation 48

Equation **48** considers the personnel who are associated with processing equipment in the waste management activity. And the personnel associated with the transporting of the residual waste for disposal is considered separately in transportation costs.

5.1.4. Storage cost ($K_{Storage}$)

Storage cost is another important parameter that has to be considered irrespective of planned production time since the storage area is utilized throughout the year for storing various kinds of materials (like scrap material, processed material, or various kinds of waste, etc.). The yearly cost of storage area and storage equipment for storing a batch of material is distributed by the total number of hours in a year. It results in storage cost per hour. Then the hourly storage cost is multiplied with the average storage time of a batch of size x and then divided with the output of the recycling plant (x_6). The storage cost per ton can be obtained.

As explained in the waste management activity section (5.1.3), the cost of resources is being distributed over the output of the recycling plant. The storage cost of a batch of size x is being distributed over the output of the recycling plant (x6).

1. **Collection and storage activity** –

In this activity, it was considered that the storage trucks would collect the scrap material and ships it to the recycling plant. Then all the collected scrap is stored in the storage area.

The storage cost per ton can be calculated as:

$$\boldsymbol{K_{storage}} = \left(\frac{Y_x.K_{Area} + K_{s.equip(x).}}{(365)\,.(24)}\right) \cdot \left(\frac{t_{avg(x)}}{x_6}\right) \qquad \textit{Equation 49}$$

Where:

Y_x = Total storage area in square meters used for storing a batch of size x.

K_{Area} = Cost of area per square meter per year.

$K_{s.equip(x).}$ = Annual cost of storage equipment used for storing a batch.

$t_{avg(X)}$ = average storage time of a batch in hours.

x = batch size of a scrap material.

Suppose a more significant number of batches of scrap material is stored in the storage area. In that case, the total storage cost associated with all those batches will be distributed over the total output generated by processing all those batches.

In collection and storing activity, storage cost for a batch of size x is considered, and we know that x includes x_2 and x_3. The storage costs for x_2 and x_3 separated in disassembly and sorting activities are being omitted. But the storage costs for the waste generated in the pre-treatment and processing activity and the formed material (X_6) have to be considered.

The storage costs associated with the pre-treatment and processing activity can be calculated as

$$K_{storage} = \left(\left(\frac{Y_x . K_{Area} + K_{s.equip(x).}}{(365)\,.(24)}\right) . \left(\frac{t_{avg(x_4)}}{x_6}\right)\right) + \left(\left(\frac{Y_x . K_{Area} + K_{s.equip(x).}}{(365)\,.(24)}\right) . \left(\frac{t_{avg(x_6)}}{x_6}\right)\right) \qquad \textit{Equation 50}$$

5.1.5. Transportation cost ($K_{Transport}$) and Material Handling cost ($K_{material\ handling}$)

Transportation cost and the material handling cost are the two other major costs that have to be considered while calculating the cost of recycling. As mentioned in section **(3.2)** transportation and material handling are involved in multiple activities. Calculating the costs associated with transportation and material handling in each activity making the equation more complex by demanding more data. Instead of calculating these costs for every activity in which they are involved, we are calculating the yearly costs associated with transportation and material handling. Then the yearly cost is distributed over the yearly output of a recycling facility (x_n) which is the total number of tonnes of material formed by a recycling facility into bars, blocks, etc., in planned production time in a year. The cost of transportation and material handling per ton can be achieved.

The yearly transportation cost considers the annual cost of transportation equipment which can be calculated using the annuity method as discussed in section **(5.1.1).** Along with the annual cost **a**, the yearly transportation cost also includes the ongoing maintenance costs (K_{MH}), renovation costs (K_{ren}), fuel costs (K_{fuel}), and also the associated personnel cost (K_D).

Therefore, the total cost of transportation per ton ($K_{Transport}$) can be calculated as

$$K_{transport} = \frac{a_f \cdot K_0 (1 + K_0 \cdot N_{ren}) + K_{MH} + K_{fuel} + K_D . N_{OP} . T_{Plan}}{x_n} \qquad \textit{Equation 51}$$

Similarly, the cost of material handling per ton can be calculated. But the major difference is, the material handling equipment occupies some area within the recycling plant. Along with all the costs mentioned below, the cost associated with the area must be considered while calculating the yearly cost of material handling.

Therefore, the total cost of material handling per ton ($K_{\text{material handling}}$) can be calculated as

$$\boldsymbol{K_{material\ handling} = \frac{a_f \cdot K_0 (1 + K_0 \cdot N_{ren}) + K_{MH} + K_{energy} + A.K_{Area} + K_D.N_{OP}.T_{Plan}}{x_n}}$$

Equation 52

Where:

a_f = annotation factor, which is calculated by using equation 6.

K_0 = basic investment.

N_{ren} = Number of renovations which is calculated by equation 9.

K_{MH} = Yearly maintenance cost

K_{fuel} = Yearly fuel cost for transport equipment.

K_{energy} = Yearly energy cost for material handling equipment.

A = The area tied to the equipment.

K_{Area} = Yearly cost of area per square meter.

X_n = Yearly output of a recycling facility which is the total number of tonnes of material formed by a recycling facility into bars, blocks, etc., in planned production time in a year.

5.1.6. Material cost (K_{Material})

Material cost is another most important parameter to be considered while calculating the cost of recycling. All the costs related to materials, either directly or indirectly, are considered under this section. The cost associated with scrap material and the virgin material is considered under direct material costs. The costs associated with additional process requirements, waste material disposal, and scrap material conversion are considered indirect material costs.

1. Direct material costs:

Indirect material costs, the total costs associated with scrap material and virgin material are considered. Initially, dedicated recycling trucks will collect the scrap and ships it to the recycling plant. Even though the collected scrap is a mixed scrap with recyclable and reusable materials, the costs associated with the whole scrap material have to be considered. Moreover, during the processing stage, depending on the results of quality inspection, recycling efficiency, and amount of solid waste generated, a suitable amount of virgin material (x_5) is added to the recycled material to get the desired output. The costs associated with virgin material also have to be considered.

The cost of scrap material ($K_{\text{Scrap Material}}$) distributed over the ton of a formed material can be evaluated by dividing the total cost of scrap material of a batch of size (x) with the output of the recycling plant (x_6) obtained by processing x tonnes of scrap material.
Therefore, the total cost of scrap material ($K_{\text{Scrap Material}}$) distributed over the ton of formed material can be calculated as

$$\boldsymbol{K_{Scrap\ Material} = \frac{K_{SM}.(x)}{x_6}} \qquad \textit{Equation 53}$$

Where:
K_{SM} = Cost of one ton of scrap material.

Similarly, the cost of virgin material ($K_{\text{Virgin Material}}$) distributed over the ton of formed material can be assessed by dividing the total cost of virgin material added during the processing of the scrap material of batch size (x) with the output of the recycling plant (x_6) obtained by processing x tonnes of scrap material.
Therefore, the total cost of virgin material ($K_{\text{Virgin Material}}$) distributed over the ton of formed material can be calculated as

$$\boldsymbol{K_{Virgin\ Material} = \frac{K_{VM}.(x_5)}{x_6}} \qquad \textit{Equation 54}$$

Where:
K_{VM} = Cost of one ton of virgin material.

2. Indirect material costs:

The costs associated with the additional process requirements involved in processing and waste management activities, the costs associated with waste disposal, and the cost associated with scrap conversion in processing activity are considered indirect material costs.

5.1.7. Costs associated with additional process requirements –

- **Pre-treatment and processing activity - (Activity 4)**

As mentioned in section 3.2.4, depending on the recycling material, the recycling process consumes reagents for converting the scrap metal into intermediate compounds, which are then processed to obtain pure metals. These chemical reagents are considering as additional process requirements (APR). The cost of APR (K_{APR}) associated with **Activity 4** can be calculated by dividing the cost of chemical reagents (K_{A4}) for processing a batch of scrap material (x) with the output of recycling plant (x_6) obtained by processing x tonnes of scrap material.
Therefore, the total cost of APR (K_{APR}) distributed over the ton of formed material can be calculated as

$$\boldsymbol{K_{APR} = \frac{K_{A4}}{x_6}} \qquad \textit{Equation 55}$$

Where:
K_{A4} = Total cost of reagents required in activity 4 for processing a batch of size x.

- **Waste management activity – (Activity 5)-**

Similarly, in the waste management activity, depending on the type of waste, the selected treatment method consumes chemical reagents to minimize the impact of waste on the environment and recover the material, and the cost associated with these reagents is considered under additional process requirements. The cost of APR (K_{APR}) associated with **Activity 5** can be calculated by dividing the cost of chemical reagents (K_{A5}) for processing the waste generated by the scrap material of batch size (x) with the output of recycling plant (x_6) obtained by processing x tonnes of scrap material.

Therefore, the total cost of APR (K_{APR}) distributed over the ton of formed material can be calculated as

$$\boldsymbol{K_{APR} = \frac{K_{A5}}{x_6}} \qquad \textit{Equation 56}$$

Where:

K_{A5} = Total cost of reagents required in activity 5 for processing the waste generated by the scrap material of batch size x.

5.1.8. Costs associated with conversion-

As mentioned in **pre-treatment and processing activity**, sometimes the scrap does not meet the desired requirements and specifications. The scrap will be re-entered into the recycling process by making some conversions which adds conversion costs, and similarly, in some recycling processes, some conversion steps are required to convert the intermediate compounds into final material, which also adds conversion costs. The conversion costs associated with **Activity 4** (pre-treatment and processing) can be calculated by dividing the total conversion cost for processing a scrap of batch size (x) with the output of the recycling plant (x_6) obtained by processing x tonnes of scrap material.

Therefore, the total conversion costs distributed over the ton of formed material can be calculated as

$$\boldsymbol{K_{conversion} = \frac{K_{CON}}{x_6}} \qquad \textit{Equation 57}$$

Where:

K_{CON} = Total conversion cost for processing the scrap of batch size (x).

Costs associated with waste material disposal:

In the waste management activity, the waste generated in pre-treatment and processing activity (x_4) is collected and treated using appropriate treatment methods and appropriate reagents to make the waste in-toxic and less harmful to the environment explained in section 3.2.5. Also, some kinds of waste, like Sludge, are treated for separating the suspended metallic particles. After treating the waste with the appropriate method, the leftover material is disposed of in the landfill, eliminating a disposal cost. The disposal costs associated with **Activity 5** (waste management) can be calculated by dividing the total disposal cost for disposing of x_7 with the output of the recycling plant (x_6) obtained by processing x tonnes of scrap material.

The total disposal cost distributed over the ton of formed material can be calculated as

$$\boldsymbol{K_{Disposal} = \frac{K_{DC}.x_7}{x_6}} \qquad \textit{Equation 58}$$

Where:

X_7 = Total number of tonnes of non-recyclable material processed hazardous waste and any other additional compounds generated while processing various kinds of waste in waste management center.

K_{DC} = Cost of disposal per ton.

5.1.7. Additional costs ($K_{Additional}$)

As mentioned in section **(3.2)**, along with the direct costs and indirect costs mentioned in Table 1, some other hidden indirect costs in the recycling process have to be considered, and these hidden costs are considered additional costs. The costs associated with quality assurance, health and safety, and any activity-specific indirect costs (like local storage or buffer cost, forming tools cost, etc.) fall under this category.

In recycling, quality assurance is one of the most important factors to be considered. In the whole recycling process, quality inspection will be done at multiple stages to ensure the quality of the material. For example, to know the quality of scrap material, inspection will be done before processing. Also, quality inspection will be done during processing, which helps add virgin material. Finally, to ensure the quality of the final material, a quality inspection will be done after processing. The quality inspection at multiple stages incurs a considerable amount of cost. But this quality assurance does not add any value to the product. It is being considered under indirect costs. The total cost of quality assurance ($K_{\text{Quality assurance}}$) distributed over the ton of formed material can be calculated by dividing the yearly cost associated with quality assurance. With the yearly output of a recycling facility (x_n), the total number of tonnes of material formed by a recycling facility into bars, blocks, etc., in planned production time in a year.

The yearly quality assurance cost considers the annual cost of quality inspection equipment which can be calculated by using the annuity method as discussed in section **(5.1.1)**. Along with the annual cost **a**, the yearly transportation cost also includes the ongoing maintenance costs (K_{MH}), renovation costs (K_{ren}), energy costs (K_{fuel}), area costs (k_{Area}), and also the associated personnel cost (K_D).

$$\boldsymbol{K_{Quality\ assurance} = \frac{a_f \cdot K_0 (1 + K_0 \cdot N_{ren}) + K_{MH} + K_{energy} + A.K_{Area} + K_D.N_{OP}.T_{Plan}}{x_n}}$$

Equation 59

Similarly, during scrap handling, hazardous waste handling, scrap processing, and waste processing precautions related to health and safety must impose costs in the form of safety equipment, first aid kits, safety channels, etc. For example, to monitor the steel melting process in the furnace, special goggles, clothes, protection mask, and helmet is required. Similarly, in various processes, various kinds of safety precautions are required. The total cost related to health and safety distributed over the ton of formed material can be calculated by dividing the yearly cost associated with health and safety with the yearly output of a recycling facility (x_n).

$$\boldsymbol{K_{Health\ and\ safety} = \frac{K_{HS}}{x_n}}$$

Equation 60

Where:

K_{HS} = Yearly costs associated with Health and safety.

Based on the literature survey, these are the identified direct and indirect costs involved in the recycling process. But in every activity, there might be chances of hidden costs like personnel training, coolants required by equipment, tools required for forming the material into blocks, local storage or buffer, etc. In this model, these costs are considered activity-specific indirect costs. They can be calculated by dividing the yearly cost associated with all the activities with the yearly output of a recycling facility (x_n).

$$\boldsymbol{K_{Indirect}} = \frac{\sum_{i=1}^{5} \boldsymbol{K_{IDC}}}{\boldsymbol{x_n}} \qquad \textit{Equation 61}$$

Where:
K_{IDC} = Yearly indirect costs associated with activities 1 to 5.

Therefore, these are the equations for calculating the various direct, indirect, and hidden costs involved in the recycling process. Few equations are considering the cost for processing a batch, and in these equations, the cost is being divided with the output of the recycling plant (x_6) obtained by processing a batch scrap material. Similarly, few equations are considering the yearly cost. In these equations, the yearly cost is being divided by the yearly output of the recycling facility (x_n). In this way, all these equations are expressing the respective cost in terms of cost per ton.

From section **(5.1.1- 5.1.7)**, cost equations are presented for calculating the cost of a particular resource associated with a specific activity. But this thesis aims to develop a model for calculating the cost of recycling per ton. In the following section, two different models for calculating the cost of recycling per ton are explained in detail.

5.1.8. Cost equations for calculating the total cost of recycling per ton.

As mentioned in section (Literature review), the developed economic model or the cost equation for calculating the cost of recycling per ton is based on the activity-based costing (ABC) model and the basic economic model for judging production development. Like the ABC model, the developed economic model initially identified the major activities involved in the recycling process (section 3.2) and then identified the resources (Table 1) consumed by the activities. Then appropriate cost drivers are chosen as explained in section 3.4. Later, as explained in the basic economic model for judging production development, the direct and indirect costs associated with the resources are coupled with performance factors, as mentioned in section 5.1. Finally, the cost associated with all the activities involved in the recycling process is added to determine the cost of recycling per ton.

Therefore, the cost of recycling per ton ($K_{\text{Recycling}}$) is calculated as

$$K_{\text{Recycling}} = K_1 + K_2 + K_3 + K_4 + K_5 + K_{\text{Material handling}} + K_{\text{Transportation}} + K_{\text{Additional}}$$

Equation 62

Where:
K_1 represents the costs associated with collection and storing activity.
K_2 represents the costs associated with disassembly activity.
K_3 represents the costs associated with shredding and sorting activity.
K_4 represents the costs associated with pre-treatment and processing activity.
K_5 represents the costs associated with waste management activity.

1. **Cost associated with collection and storing activity –**

The cost associated with collection and storage activity can be calculated as

$$K_1 = K_{Scrap\ material} + K_{Personnel} + K_{storage}$$

Equation 63

Therefore,

$$\boldsymbol{K_1 = \left(\left(\frac{K_{SM}.(x)}{x_6}\right) + \left(\frac{K_D.N_{OP}}{x_n}(T_{Plan})\right) + \left(\frac{Y_x.K_{Area} + K_{s.equip(x).}}{(365)\,.(24)}\right).\left(\frac{t_{avg(X)}}{x_6}\right)\right)}$$

Equation 64

2. Cost associated with disassembly activity –

The cost associated with disassembly activity can be calculated as

$\boldsymbol{K_2 = K_{Equipment} + K_{Personnel}}$ *Equation 65*

Therefore,

$$\boldsymbol{K_2} = \left(\frac{\boldsymbol{K_{CP}}}{(\boldsymbol{x_1}+\boldsymbol{x_3})}\left(\frac{\boldsymbol{t_0} \cdot \boldsymbol{x}}{(\boldsymbol{1}-\boldsymbol{q_p})}\right) + \frac{\boldsymbol{K_{CS}}}{(\boldsymbol{x_1}+\boldsymbol{x_3})}\left(\frac{\boldsymbol{t_0} \cdot \boldsymbol{x}}{(\boldsymbol{1}-\boldsymbol{q_p})} \cdot \frac{\boldsymbol{q_s}}{(\boldsymbol{1}-\boldsymbol{q_s})} + \boldsymbol{T_{su}}\right)\right) + \left(\frac{\boldsymbol{K_D} \cdot \boldsymbol{N_{OP}}}{(\boldsymbol{x_1}+\boldsymbol{x_3})}\left(\frac{\boldsymbol{t_0} \cdot \boldsymbol{x}}{(\boldsymbol{1}-\boldsymbol{q_p}) \cdot (\boldsymbol{1}-\boldsymbol{q_s})} + \boldsymbol{T_{su}}\right)\right)$$

Equation 66

3. Cost associated with shredding and sorting activity –

The cost associated with shredding and sorting activity can be calculated as

$K_3 = K_{Equipment} + K_{Personnel}$ *Equation 67*

Therefore,

$$\boldsymbol{K_3} = \left(\frac{\boldsymbol{K_{CP}}}{(\boldsymbol{x_1})}\left(\frac{\boldsymbol{t_0} \cdot (\boldsymbol{x_1}+\boldsymbol{x_3})}{(\boldsymbol{1}-\boldsymbol{q_p})}\right) + \frac{\boldsymbol{K_{CS}}}{(\boldsymbol{x_1})}\left(\frac{\boldsymbol{t_0} \cdot (\boldsymbol{x_1}+\boldsymbol{x_3})}{(\boldsymbol{1}-\boldsymbol{q_p})} \cdot \frac{\boldsymbol{q_s}}{(\boldsymbol{1}-\boldsymbol{q_s})} + \boldsymbol{T_{su}}\right)\right) + \left(\frac{\boldsymbol{K_D} \cdot \boldsymbol{N_{OP}}}{(\boldsymbol{x_1})}\left(\frac{\boldsymbol{t_0} \cdot (\boldsymbol{x_1}+\boldsymbol{x_3})}{(\boldsymbol{1}-\boldsymbol{q_p}) \cdot (\boldsymbol{1}-\boldsymbol{q_s})} + \boldsymbol{T_{su}}\right)\right)$$

Equation 68

4. Cost associated with pre-treatment and processing activity –

The cost associated with pre-treatment and processing activity can be calculated as

$\mathrm{K_4 = K_{virgin\ material} + K_{Equipment} + K_{Personnel} + K_{APR} + K_{conversion} + K_{storage}}$

Equation 69

Therefore,

$$\boldsymbol{K_4 = \Big(\frac{K_{VM}.(x_5)}{x_6}\Big) + \Bigg(\frac{K_{CP}}{(x_6)}\bigg(\frac{t_0.\ (x_1)}{(1-q_p)}\bigg) + \frac{K_{CS}}{(x_6)}\bigg(\frac{t_0.\ (x_1)}{(1-q_p)} .\ \frac{q_s}{(1-q_s)} + T_{su}\bigg)\Bigg) +}$$

$$\boldsymbol{\Bigg(\frac{K_D.\ N_{OP}}{(x_6)}\bigg(\frac{t_0.\ (x_1)}{(1-q_p).\ (1-q_s)} + T_{su}\bigg)\Bigg) + \frac{K_{A4}}{x_6} + \frac{K_{CON}}{x_6} +}$$

$$\boldsymbol{+ \Bigg(\Bigg(\bigg(\frac{Y_x.K_{Area} + K_{s.equip(x).}}{(365)\ .(24)}\bigg) . \bigg(\frac{t_{avg(x_4)}}{x_6}\bigg)\Bigg)\Bigg) +}$$

$$\boldsymbol{\Bigg(\bigg(\frac{Y_x.K_{Area} + K_{s.equip(x).}}{(365)\ .(24)}\bigg) . \bigg(\frac{t_{avg(x_6)}}{x_6}\bigg)\Bigg)\Bigg)} \qquad \textit{Equation 70}$$

5. Cost associated with waste management activity –

The cost associated with waste management activity can be calculated as

$$K_5 = K_{Equipment} + K_{Personnel} + K_{APR} + K_{Disposal} \qquad \textit{Equation 71}$$

Therefore,

$$\boldsymbol{K_5 = \Bigg(\frac{K_{CP}}{(x_6)}\bigg(\frac{t_0.\ (x_3)}{(1-q_p)}\bigg) + \frac{K_{CP}}{(x_6)}\bigg(\frac{t_0.\ (x_4)}{(1-q_p)}\bigg) + \frac{K_{CS}}{(x_6)}\bigg(\frac{t_0.\ (x_3)}{(1-q_p)} .\ \frac{q_s}{(1-q_s)} + T_{su}\bigg) +}$$

$$\boldsymbol{\frac{K_{CS}}{(x_6)}\bigg(\frac{t_0.\ (x_4)}{(1-q_p)} .\ \frac{q_s}{(1-q_s)} + T_{su}\bigg)\Bigg) + \Bigg(\frac{K_D.\ N_{OP}}{(x_6)}\bigg(\frac{t_0.\ (x_3)}{(1-q_p).\ (1-q_s)} + T_{su}\bigg) +}$$

$$\boldsymbol{\frac{K_D.\ N_{OP}}{(x_6)}\bigg(\frac{t_0.\ (x_4)}{(1-q_p).\ (1-q_s)} + T_{su}\bigg)\Bigg) + \frac{K_{A5}}{x_6} + \frac{K_{DC}.x_7}{x_6}} \qquad \textit{Equation 72}$$

6. Cost associated with material handling –

The cost associated with the material handling can be calculated as

$$K_{Material\ Handling} = \frac{a_f \cdot K_0(1 + K_0 \cdot N_{ren}) + K_{MH} + K_{energy} + A.K_{Area} + K_D.N_{OP}.T_{Plan}}{x_n}$$

Equation 73

7. Cost associated with transportation –

The cost associated with the transportation can be calculated as

$$K_{Transport} = \frac{a_f \cdot K_0(1 + K_0 \cdot N_{ren}) + K_{MH} + K_{fuel} + K_D . N_{OP} . T_{Plan}}{x_n}$$

Equation 74

8. Costs considered under additional costs –

The costs that fall under additional costs can be calculated as

$K_{Additional} = K_{Quality\ Assurance} + K_{Health\ and\ safety} + K_{Indirect}$

Equation 75

Therefore,

$$\boldsymbol{K_{Additional} = \left(\frac{a_f \cdot K_0(1+K_0 \cdot N_{ren})+K_{MH}+K_{energy}+A.K_{Area}+K_D.N_{OP}.T_{Plan}}{x_n}\right) + \frac{K_{HS}}{x_n} + \frac{\sum_{i=1}^{5} K_{IDC}}{x_n}}$$

Equation 76

From the above equation, we can calculate the cost of recycling per ton by calculating the costs associated with every activity involved in recycling. Suppose one would like to know about the costs associated with a particular resource group, like the total cost of materials or the cost of total equipment involved in the recycling plant. In that case, the cost for recycling a ton of the material can be calculated by using the **following equation**.

$K_{Recycling} = K_{Materials} + K_{Equipment} + K_{Personnel} + K_{material\ handling} + K_{Transportation} + K_{Storage} + K_{Additional}$

Equation 77

Where:

$K_{Materials}$ represent the cost associated with direct and indirect materials.

$K_{Equipment}$ represents the cost associated with all the processing equipment involved in all the activities.

$K_{Personnel}$ represents the cost associated with all the personnel involved in all the major activities. Personnel cost associated with transportation and material handling is excluded.

$K_{Material\ handling}$ represents the cost associated with material handling systems involved in between all the activities and in between the various activities and storage.

$K_{Transportation}$ represents the cost associated with transportation involved in activities 1 and 5.

$K_{Storage}$ represents the cost associated with storage involved in activities 1 and 4.

$K_{Additional}$ represents the cost associated with quality assurance, health and safety, and any activity based indirect costs.

1. **Cost associated with materials** –

The cost associated with the materials ($K_{Materials}$) can be calculated by adding up the cost of scrap material, virgin material, additional processing requirements, disposal costs, and conversion costs. The appropriate equations for calculating each of these costs are mentioned in section Material cost ($K_{Material}$).

2. **Cost associated with equipment** –

The cost associated with the equipment can be calculated by adding the cost of all the processing equipment involved in **Activity 1**,2, 3, 4, and 5. The equations for calculating the cost of processing equipment involved in all these activities are mentioned in section 5.1.3.

3. **Cost associated with personnel** –

The cost associated with the personnel can be calculated by adding the cost of all the personnel involved in **Activity 1**, 2, 3, 4, and 5. The equations for calculating the cost of personnel involved in all these activities are mentioned in sections 5.1.2 and 5.1.3. But in this cost, the personnel involved in transportation and material handling is not considered since it was considered in the costs associated with transportation and material handling.

4. **Cost associated with transportation and material handling** –

As mentioned in section 3.3, transportation and material handling are involved in multiple activities. Calculating the costs associated with transportation and material handling in each activity making the equation more complex by demanding more data. Instead of calculating these costs for every activity in which they are involved, we are considering them for the whole recycling process. The equations for calculating these costs are mentioned in section 5.1.5.

5. **Cost associated with storage** –

The cost associated with storage can be calculated by adding the cost of storage involved in **Activity 1** and **Activity 4**. The equations for calculating the cost of storage involved in these activities are mentioned in the section Storage cost ($K_{Storage}$). There might be chances of the presence of local warehouses or buffers, and the cost associated with this local storage is considered under activity-specific price, which falls under additional cost.

6. **Costs considered under additional cost –**

The cost associated with this additional cost is calculated by adding the cost of quality assurance, health and safety, and activity-specific indirect costs. The equations for calculating these respective costs are mentioned in section 5.1.7.

These are the two models for calculating the cost of recycling per ton. Both the models give the exact cost for recycling a ton of material but choosing an appropriate model depends upon the type of study and type of results required. For example, suppose a recycling industry would like to analyze the total annual cost associated with the equipment. In that case, it can choose the model which was built by considering resource groups. Similarly, if a recycling industry wants to analyze the cost associated with waste management, the industry can choose the model created by considering activities.

The following section explains the cost equations for calculating the costs associated with various resource groups involved in the remanufacturing process and presents the cost equations for calculating the cost of remanufacturing per product.

5.2. Cost equations associated with the remanufacturing process.

As mentioned in section 4.4, there are eight resource groups- processing equipment, personnel, materials, tools, material handling, storage area, additional process requirements, and additional costs in the remanufacturing process. The costs associated with each resource group play a crucial role in the total cost of remanufacturing. The cost associated with each resource group can be calculated as explained below.

5.2.1. Processing equipment cost ($K_{Equipment}$)

The cost of processing equipment is one of the major direct costs that must be considered while calculating the cost of remanufacturing. In the remanufacturing process, the cost associated with the equipment will be calculated in the same way as the recycling process. Initially, hourly equipment cost when running and when idle is calculated using Equation **29** and **30**. The equipment hourly cost is multiplied by the total time for processing a batch in a particular activity and then divided with the Output of that activity so that the equipment cost per product can be achieved.

Equation **34** mentioned in section 5.1.1 is used for calculating the equipment cost per ton of material. But the same equation can be used for calculating the equipment cost per product only if x_{in} is replaced with N_{in} and x_{out} is replaced with N_{out}.

Therefore,

$$\boldsymbol{K_{Equipment}} = \frac{\boldsymbol{K_{CP}}}{\boldsymbol{N_{out}}}\left(\frac{\boldsymbol{t_0 \cdot N_{in}}}{\boldsymbol{(1-q_p)}}\right) + \frac{\boldsymbol{K_{CS}}}{\boldsymbol{N_{out}}}\left(\frac{\boldsymbol{t_0 \cdot N_{in}}}{\boldsymbol{(1-q_p)}} \cdot \frac{\boldsymbol{q_s}}{\boldsymbol{(1-q_s)}} + \boldsymbol{T_{su}}\right) \qquad \textit{Equation 78}$$

Where:

N_{in} = Total number of parts or products entered into a particular activity, and it can also be called the batch size of that activity.

N_{out} = Output of a particular activity in terms of either parts or products.

5.2.2. Personnel cost ($K_{Personnel}$)

Similar to the equipment cost, the personnel cost per hour is taken. Then it is multiplied with the total time for processing a batch in a particular activity and then divided with the Output of that activity so that the personnel cost per product can be achieved.

Equation 35 mentioned in section 5.1.2 is used for calculating the personnel cost per ton of material. But the same equation can be used for calculating the equipment cost per product only if x_{in} is replaced with N_{in} and x_{out} is replaced with N_{out}.

Therefore,

$$\boldsymbol{K_{Personnel}} = \frac{\boldsymbol{K_D \cdot N_{OP}}}{\boldsymbol{N_{out}}}\left(\frac{\boldsymbol{t_0 \cdot N_{in}}}{\boldsymbol{(1-q_p) \cdot (1-q_s)}} + \boldsymbol{T_{su}}\right) \qquad \textit{Equation 78}$$

5.2.3. Equipment and personnel costs for each activity

From the above equations, the total number of parts or products entering a particular activity and the Output of that activity plays a crucial role in determining the equipment and personnel costs associated with that activity. To understand the costs associated with each activity in detail, the following assumptions are considered.

- N is the total number of products collected from the warehouse for remanufacturing, and it can also be called as product's batch size.
- We know that a product contains Z number of various parts (For example, an engine contains a crankshaft, camshaft, pistons, valves, cylinder head………...Z). For the N number of products, N_i represents the batch size of a specific part.
- As mentioned in section 4.2, few parts will be rejected in inspection 1 because the parts do not meet the required standards and specifications. N_{0i} represents the number of parts of a specific type that have qualified the inspection 1.
- In a product, out of various parts, few parts are in multiple numbers (For example, eight pistons in a V8 engine). N_{sp} represents the number of parts of a specific type used in a single product.
- N_{Reman} represents the number of remanufactured parts used in a product.
- $N_{New/Used}$ represents the number of used or new parts used in a product.

To understand these terms in detail, a small example is illustrated below,

For example, 10 V8 engines are taken from the warehouse for remanufacturing. As we know that, every engine contains eight pistons. Ten engines include 80 pistons in total. But out of 80 pistons, only 70 pistons have qualified inspection 1 and entered into machining and material addition activity, and the remaining ten pistons are rejected and considered scrap. Now, these rejected ten pistons are replaced with new pistons. The ten engines are assembled back in the assembly activity.
Similarly, every engine contains one crankshaft. Ten engines contain 160 valves. Out of 160, only 140 valves have qualified the inspection 1 and entered into machining and material addition activity. The remaining 20 valves are rejected and considered as scrap. Now, the rejected valves are replaced with a new one's. The ten engines are assembled back in the assembly activity.
From the example,
The batch size of a product (N) = 10.

For pistons

- The number of parts of a certain kind used in a single product $\mathbf{N}_{sp}$ = 8.
- For ten products, the batch size of pistons, $\mathbf{N}_1$ = 80.
- The number of parts of a certain kind has qualified the inspection 1, $\mathbf{N}_{01}$ = 70.
- Let's say every engine is assembled with seven remanufactured pistons and with one new piston. Therefore, the number of remanufactured parts used in a product, $\mathbf{N}_{\mathbf{Reman}}$ **is seven,** and the number of used or new parts used in a product, $\mathbf{N}_{\mathbf{New/Used}}$ **= 1**

For valves

- The number of parts of a certain kind used in a single product $\mathbf{N}_{sp}$ = 16.
- For ten products, the batch size of valves, $\mathbf{N}_2$ = 160.
- The number of parts of a certain kind has qualified the inspection 1, $\mathbf{N}_{01}$ = 140.
- Let's say every engine is assembled with 14 remanufactured valves and with two new valves. Therefore, the number of remanufactured parts used in a product, $\mathbf{N}_{\mathbf{Reman}}$ **is 14,** and the number of used or new parts used in a product, $\mathbf{N}_{\mathbf{New/Used}}$ **= 2**

For the same product's batch size, various batch sizes for multiple parts used in a product are observed. It is important to consider multiple batch sizes since batch size plays a crucial role in calculating the processing time, affecting the equipment cost and personnel cost.

Considering that the 'N' number of products are collected from the warehouse for remanufacturing, every specific part of each product is processed. The total number of parts of a particular type of part rejected in inspection is replaced with the same number of used or new parts of that type. The N number of products are assembled back in assembly activity, therefore**, the Output of the remanufacturing process will be N.**

1. **Stage 1 –**

In the remanufacturing facility, the remanufacturing process starts with disassembly activity. As mentioned, a batch of products of size N is given as input to disassembly activity. In this activity, all the products are dismantled, and then the parts are separated and sent to **Stage 2**. As mentioned in section 4.2, in disassembly activity, the cost associated with tools and fixtures is considered additional process requirements. There will be no cost associated with equipment in this activity, and only personnel cost is observed. The total personnel cost associated with disassembly activity will be distributed over the Output of the whole remanufacturing process, i.e., N, which results in a **cost per product**.

For disassembly activity

- $N_{in} = N_{out} = N$

Therefore,

The personnel cost per product can be calculated as

$$\frac{\boldsymbol{K_D \cdot N_{OP}}}{\boldsymbol{N}}\left(\frac{\boldsymbol{t_0 \cdot N}}{\boldsymbol{(1-q_p) \cdot (1-q_s)}} + \boldsymbol{T_{su}}\right) \qquad \textit{Equation 79}$$

2. **Stage 2 –**

In **Stage 2**, every part included in a product will be processed. Initially, N_i number of parts of a specific type are taking as input for cleaning and inspection activities. But out of them, only N_{0i} number of parts are qualified in **Inspection 1** and entered into further processing station, i.e., machining and material addition activity. The input for **Machining and Material addition** and **Inspection 2** activities is N_{0i}. Considering that N_{0i} number of parts are machined, and a suitable amount of material added, they are qualified inspection 2. The Output of inspection two will be N_{0i} which is also the Output of stage 2. The equipment and personnel costs associated with every activity in stage 2 will be distributed over N_{0i}, which results in a **cost per part**.

Based on the example mentioned above, 80 pistons are given as an input to cleaning and inspection 1 activities. In inspection 1, out of 80 pistons, only 70 pistons met the requirements. These 70 pistons are processed in machining and material addition activity, and they have qualified inspection two as well. The remaining ten pistons are considered scrap. The Output of inspection two will be the Output of stage 2 which is 70 pistons.

Therefore, the equipment and personnel costs associated with **Stage 2** can be calculated as

Cleaning activity –

For cleaning activity,

- $N_{in} = N_i$
- $N_{out} = N_{0i}$

Therefore,

The equipment cost per part of specific type during processing:

$$\frac{K_{CP}}{N_{0i}}\left(\frac{t_0 \cdot N_i}{(1-q_p)}\right) \qquad \textit{Equation 80}$$

The equipment cost per part of specific type during standstill:

$$\frac{K_{CS}}{N_{0i}}\left(\frac{t_0 \cdot N_i}{(1-q_p)} \cdot \frac{q_s}{(1-q_s)} + T_{su}\right) \qquad \textit{Equation 81}$$

The personnel cost per part of specific type:

$$\frac{K_D \cdot N_{OP}}{N_{0i}}\left(\frac{t_0 \cdot N_i}{(1-q_p) \cdot (1-q_s)} + T_{su}\right) \qquad \textit{Equation 82}$$

Inspection 1 –

For inspection 1,

- $N_{in} = N_i$
- $N_{out} = N_{0i}$

Therefore,

The equipment cost per part of specific type during processing:

$$\frac{K_{CP}}{N_{0i}}\left(\frac{t_0 \cdot N_i}{(1-q_p)}\right) \qquad \textit{Equation 83}$$

The equipment cost per part of specific type during standstill:

$$\frac{K_{CS}}{N_{0i}}\left(\frac{t_0.N_i}{(1-q_p)}\cdot\frac{q_s}{(1-q_s)}+T_{su}\right)$$ *Equation 84*

The personnel cost per part of specific type:

$$\frac{K_D.\ N_{OP}}{N_{0i}}\left(\frac{t_0.\ N_i}{(1-q_p).\ (1-q_s)}+T_{su}\right)$$

Equation 85

Machining and material addition activity –
For machining and material addition activity,

- $N_{in} = N_{0i}$
- $N_{out} = N_{0i}$

Therefore,
The equipment cost per part of specific type during processing:

$$\frac{K_{CP}}{N_{0i}}\left(\frac{t_0.\ N_{0i}}{(1-q_p)}\right)$$ *Equation 86*

The equipment cost per part of specific type during standstill:

$$\frac{K_{CS}}{N_{Oi}}\left(\frac{t_0.N_{0i}}{(1-q_p)}\cdot\frac{q_s}{(1-q_s)}+T_{su}\right)$$ *Equation 87*

The personnel cost per part of specific type:

$$\frac{K_D.\ N_{OP}}{N_{0i}}\left(\frac{t_0.\ N_{0i}}{(1-q_p).\ (1-q_s)}+T_{su}\right)$$ *Equation 88*

Inspection 2 –
For inspection 2 activity,

- $N_{in} = N_{0i}$
- $N_{out} = N_{0i}$

Therefore,
The equipment cost per part of specific type during processing:

$$\frac{K_{CP}}{N_{Oi}}\left(\frac{t_0.\ N_{0i}}{(1-q_p)}\right)$$ *Equation 89*

The equipment cost per part of specific type during standstill:

$$\frac{K_{CS}}{N_{Oi}}\left(\frac{t_0 . N_{0i}}{(1-q_p)} \cdot \frac{q_s}{(1-q_s)} + T_{su}\right) \qquad \textit{Equation 90}$$

The personnel cost per part of specific type:

$$\frac{K_D . N_{OP}}{N_{Oi}}\left(\frac{t_0 . N_{0i}}{(1-q_p).(1-q_s)} + T_{su}\right) \qquad \textit{Equation 91}$$

All the equipment and personnel costs associated with **Stage 2** will express the cost in terms of cost per part. While calculating the cost of remanufacturing per product, these costs have to be considered in terms of cost per product, and the equation for calculating these in terms of cost per product is explained in **Machining and Material addition (K_{MM}):**

All the processed parts are entered into **Stage 3** , and all the rejected parts are replaced with either new parts or used parts.

3. Stage 3 –

In this stage, all the parts from **Stage 2** are collected, and the rejected parts are replaced with new ones or used ones, and then all the parts are assembled into products. Then each product undergoes rigorous testing in functional testing activity, and then all the products are applied with appropriate protective coatings.

Assembly activity –

In assembly activity, by collecting all the parts, N number of products are assembled into final products. The total time for assembling N number of products has to be taken into account while calculating the personnel cost. As mentioned in section 4.2, in assembly activity, the cost associated with tools and fixtures are considered under additional process requirements. In this activity, there will be no cost associated with equipment, and only personnel cost is observed, and the total personnel cost associated with assembly activity will be distributed over the Output of the whole remanufacturing process, i.e., N, which results in a **cost per product**.

For assembly activity

- $N_{in} = N_{out} = N$

Therefore,

The personnel cost per product can be calculated as

$$\frac{K_D .\ N_{OP}}{N}\left(\frac{t_0 .\ N}{(1-q_p).\ (1-q_s)} + T_{su}\right) \qquad \textit{Equation 92}$$

Functional testing activity –

In this activity, all the products are subjected to all the tests that a new product has been through to make sure that the products are ready for real-life application. In this activity, the total time for testing the whole batch has to be considered while calculating the cost associated with personnel and equipment, and the whole cost will be divided over the Output of remanufacturing process, i.e., N, which gives the cost per product.

For functional testing activity

- $N_{in} = N_{out} = N$

Therefore,

The equipment cost per product during processing can be calculated as

$$\frac{K_{CP}}{N}\left(\frac{t_0 .\ N}{(1-q_p)}\right) \qquad \textit{Equation 93}$$

The equipment cost per product during standstill can be calculated as

$$\frac{K_{CS}}{N}\left(\frac{t_0 .\ N}{(1-q_p)} . \frac{q_s}{(1-q_s)} + T_{su}\right) \qquad \textit{Equation 94}$$

The personnel cost per product can be calculated as

$$\frac{K_D .\ N_{OP}}{N}\left(\frac{t_0 .\ N}{(1-q_p).\ (1-q_s)} + T_{su}\right) \qquad \textit{Equation 95}$$

Painting activity –

In this activity, all the products are applied with protective coatings or new paints, etc., to protect them from the external environment. In this activity also, the total time for processing the whole batch has to be considered while calculating the cost associated with personnel and equipment, and the whole cost will be divided over the Output of remanufacturing process, i.e., N, which gives the cost per product.

For the painting activity

- $N_{in} = N_{out} = N$

Therefore,

$$\frac{K_{CP}}{N}\left(\frac{t_0 .\ N}{(1-q_p)}\right)$$ *Equation 96*

The equipment cost per product during standstill can be calculated as

$$\frac{K_{CS}}{N}\left(\frac{t_0 .\ N}{(1-q_p)} \cdot \frac{q_s}{(1-q_s)} + T_{su}\right)$$ *Equation 97*

The personnel cost per product can be calculated as

$$\frac{K_D .\ N_{OP}}{N}\left(\frac{t_0 .\ N}{(1-q_p) .\ (1-q_s)} + T_{su}\right)$$ *Equation 98*

5.2.4. Material cost ($K_{material}$)

Material cost is another most important parameter that has to be considered in the cost of remanufacturing. In this section, the cost related to used products, the cost related to material consumed in machining and material addition activity, and the cost related to surface coatings, protective layers, paintings is taken into consideration.

Cost associated with used products –

Generally, in remanufacturing process, the used products will reach the distributors from customers. Then the distributors will inspect the product, and if the product meets certain requirements and specifications, then the distributors will buy the product from the customer. Based on the condition of the product, the cost of each product varies. That's why to get the average cost of a used product, the sum of the cost of N products is being considered, and then distributing this cost over N products.

Therefore,
The average cost of a used product (K_{old}) can be calculated as

$$\boldsymbol{K_{old}} = \frac{\sum_{i=1}^{N} \boldsymbol{K_M}}{\boldsymbol{N}}$$

Equation 99

Where:
K_M = cost of a product brought from the customer.

Cost associated with material consumed in machining and material addition activity-

In machining and material addition activity, N_{0i} number of parts of a specific type is being processed. But there is no evidence that every part requires the same amount of material to be added. Based on the type of issues identified in inspection 1, appropriate processing techniques are chosen. Based on the techniques chosen, some parts might require more amount of material and some require less. Instead of taking material cost for every part, the total material cost for processing N_{0i} number of parts of a specific part type is being considered, and that cost is distributed over the Output of **Stage 2**, i.e., N_{0i}.

Therefore,
The cost of material per part can be calculated as

$$\boldsymbol{K_{Material}} = \frac{\boldsymbol{K_B}}{\boldsymbol{N_{0i}}}$$

Equation 100

Where:
K_B = Total material cost for processing N_{0i} number of parts of a specific part type.

The above-mentioned equation helps in calculating the cost of material associated with a specific part type. But in a product, there is Z number of various parts. The material cost associated with various part types has to be considered individually, which is explained in detail in section 5.2.9.

Cost associated with surface coatings, paints, and protective layers-

In the remanufacturing process, either before assembly or after assembly, the product and the parts are applied with appropriate surface coatings, protective layers, and paints. The cost associated with these paints and protective coatings has to be taken into consideration.

Similar to the material cost in material addition activity, the total cost of coatings and paintings for processing a batch of size (N) is considered, and then the total cost is divided with batch size to get the cost per product.

Therefore,

The cost of paints and coatings per product can be calculated as

$$\boldsymbol{K_{paint/coating} = \frac{K_p}{N}} \qquad \text{Equation 101}$$

Where:

K_p = Total cost of coatings and paintings for the whole batch of size (N).

5.2.5. Tool cost (K_{Tool})

Generally, defects such as cracks, nicks, burnt regions, and inclusions can be removed by various machining processes such as turning, milling, drilling, boring, grinding, etc. Based on the type of issues identified in **Inspection 1**, an appropriate machining process is selected. In these machining operations, various tools like turning tools, drilling tools, milling tools, boring tools, etc., are used for material removal purposes. The cost associated with these tools is another most important parameter that has to be considered. Similar to the material cost in machining and material addition activity, the total tool cost for processing N_{0i} number of parts of a specific part type is being considered, and that cost is distributed over the Output of **Stage 2**, i.e., N_{0i}. The cost of tools per part can be achieved.

Therefore,

The cost of tools per part can be calculated as

$$\boldsymbol{K_{Tool} = \frac{K_T}{N_{0i}}} \qquad \text{Equation 102}$$

Where:
K_T = Total tool cost for processing N_{0i} number of parts of a specific part type.

The above-mentioned equation helps in calculating the cost of tools associated with a specific part type. But in a product, there is Z number of various parts. The material cost associated with various part types has to be considered individually, which is explained in detail in section 5.2.9

5.2.6. Storage cost ($K_{storage}$)

Storage cost is another important parameter that has to be considered irrespective of planned production time since the storage area is utilized throughout the year for storing various products. That's why the yearly cost of storage area and storage equipment for storing a batch of products is distributed by the total number of hours in a year. It results in storage cost per hour. Then the hourly storage cost is multiplied with the average storage time of a batch of size N and then divided with Output of the remanufacturing plant (N). The storage cost per product can be obtained.

Therefore,
The storage cost per product can be calculated as

$$\boldsymbol{K_{storage(N)}} = \left(\frac{\boldsymbol{Y_N . K_{Area} + K_{s.equip(N).}}}{\boldsymbol{(365)\,.(24)}}\right) . \left(\frac{\boldsymbol{t_{avg(N)}}}{\boldsymbol{N}}\right) \qquad \textit{Equation 103}$$

Where:
Y_N = Total storage area in square meters used for storing a batch of size N.
K_{Area} = cost of area per square meter per year.
$K_{s.equip(N).}$ = Annual cost of storage equipment used for storing a batch of size N.
$t_{avg(N)}$ = Average storage time of a batch in hours.
N = Product's batch size.

If the greater number of batches are stored in the storage area, then the total storage cost associated with all those batches will be distributed over the total Output generated by processing all those batches.

Generally, in a remanufacturing industry, along with the products, various parts like rejected parts or spare parts will also be stored in the warehouse. In **Stage 2**, after inspection 1, if the parts of a specific type meet the requirements, then they will be transferred to machining and material addition activity; otherwise, they will be rejected and considered as scrap. At the end of **Stage 2**, these rejected parts should be replaced with either new or used parts. To facilitate the assembly process, these new parts should be readily available in the warehouse. The storage cost associated with these spare parts has also be taken into account. To understand it in more detail, the following assumptions are taken into consideration.

- N_P represents the batch size of spare parts.
- Y_{N_P}= Total storage area in square meters used for storing a batch of size N_p.
- K_{Area} = cost of area per square meter per year.
- $K_{s.equip(Np).}$ = Annual cost of storage equipment used for storing a batch of size N_P.
- $t_{avg(Np)}$ = Average storage time of a batch in hours.

Therefore,
The storage cost per part of a specific type can be calculated as

$$\boldsymbol{K_{storage(N_p)}} = \left(\frac{\boldsymbol{Y_{N_p}.K_{Area} + K_{s.equip(N_p)}}}{\mathbf{(365)\,.(24)}}\right) \cdot \left(\frac{\boldsymbol{t_{avg(N_p)}}}{\boldsymbol{N_p}}\right) \qquad \textit{Equation 104}$$

With the above equation, the storage cost per part of a specific type can be calculated. But the storage cost should be in terms of cost per product. To get the cost of storage per product, the above equation is being multiplied by number of new parts used in a product ($N_{New/used}$).

Therefore,
The storage cost per product can be calculated as

$$(\boldsymbol{N_{New/Used}}) \cdot (\boldsymbol{K_{storage(N_p)}}) \qquad \text{Equation 105}$$

With this equation, a storage cost per product for a specific part type can be calculated. But a product contains Z number of various parts, which means the Z number of various types of spare parts should be stored in a warehouse. The storage cost associated with all the spare parts of different types should be considered, and it can be calculated as

$$\sum_{i=1}^{Z} (\boldsymbol{N_{New/Used}}) \cdot \left(\frac{\boldsymbol{Y_{N_p} . K_{Area} + K_{s.equip(N_p)}}}{\boldsymbol{(365) . (24)}} \right) \cdot \left(\frac{\boldsymbol{t_{avg(N_p)}}}{\boldsymbol{N_p}} \right) \qquad \text{Equation 106}$$

5.2.7. Material handling cost ($K_{\text{material handling}}$)

Material handling is another major factor that has to be considered while calculating the cost of remanufacturing. As mentioned in section 4.2, in remanufacturing process, material handling is required for transporting the cores and parts between various activities and between activities and storage area. Calculating the costs associated with material handling in each activity making the equation more complex by demanding more data. That's why instead of calculating the material handling costs for every activity in which it is involved, we are calculating the yearly costs associated with material handling, and then the yearly cost is distributed over the yearly Output of a remanufacturing facility. The cost of material handling per product can be achieved.

The yearly material handling cost considers the annual cost of a material handling equipment which can be calculated by using the annuity method as discussed in section 5.1.1. Along with the annual cost **a**, the yearly material handling cost also includes the ongoing maintenance costs (K_{MH}), renovation costs (K_{ren}), fuel costs (K_{fuel}), area costs (K_{Area}), and also the associated personnel cost (K_D).

Therefore, the total cost of material handling per product ($K_{\text{Material Handling}}$) can be calculated as

$$\boldsymbol{K_{Material\ Handling}} = \frac{\boldsymbol{a_f \cdot K_0 (1 + K_0 \cdot N_{ren}) + K_{MH} + K_{fuel} + Y . K_{Area} + K_D . N_{OP} . T_{Plan}}}{\boldsymbol{N . n}}$$

Equation 107

Where:
a_f = annotation factor, which is calculated by using equation 6.
K_0 = basic investment.
N_{ren} = number of renovations which is calculated by equation 9.
K_{MH} = Yearly maintenance cost
K_{energy} = Yearly energy cost for equipment.
A = The area tied to the material handling equipment.
K_{Area} = Yearly cost of area per square meter.
N_{op} = number of operators involved in material handling.
K_D = Operator cost per hour.
N = product's batch size.
n = total number of batches handled in planned production time (T_{plan}).

5.2.8. Additional process requirements (K_{APR}) and additional costs ($K_{Additional}$)

As mentioned in Table 3, in remanufacturing, additional process requirements are involved in multiple activities. Out of all the activities, the additional process requirements involved in cleaning, machining, and material addition activities are considered under direct costs, and the additional process requirements involved in disassembly, assembly, functional testing, and painting are considered under indirect costs. The costs associated with these additional process requirements are calculated as explained below.

For Disassembly activity – (Activity 1)

In this activity, during disassembly, the product has to be held with appropriate fixtures, and the product should be disassembled with some tools like spanners, for example. Here, the cost associated with these fixtures and the tools is considered under additional process requirements, which falls under the indirect category since these resources do not add any value to the product. The cost of APR (K_{APR}) associated with activity 1 can be calculated by dividing the yearly cost of tools and fixtures (K_{A1}) with the yearly Output of remanufacturing plant.

Therefore, for disassembly activity, the total cost of APR (K_{APR}) per product can be calculated as

$$\boldsymbol{K_{APR} = \frac{K_{A1}}{N.n}} \qquad \textit{Equation 108}$$

Where:

K_{A1} = Yearly cost associated with tools and fixtures involved in disassembly activity.

For cleaning activity – (Activity 2)

Based on the type of product, an appropriate cleaning process is selected. Organic solvent cleaning technology, Jet cleaning technology, Thermal cleaning technology, Ultrasonic cleaning technology, and Electrolytic cleaning technology are the most common cleaning technologies used in remanufacturing process. In these cleaning technologies, various cleaning mediums like an organic solvent, detergent, acid solution, alkali solution, various solid particles are used for making the parts free from contaminants. The cleaning medium is another important resource to be considered, and it is considered under additional process requirements (APR), but in this case, the APR falls under the direct cost category since it adds some value to the parts. The cost of APR (K_{APR}) associated with activity 2 can be calculated by dividing the cost of the chemical medium for processing a N_i number of parts of a specific type with Output of stage 2, i.e., N_{0i}.

Therefore, for cleaning activity, the total cost of APR (K_{APR}) per part of a specific type can be calculated as

$$\boldsymbol{K_{APR} = \frac{K_{A2}}{N_{0i}}} \qquad \textit{Equation 109}$$

Where:

K_{A2} = cost associated with cleaning medium for processing N_i number of parts of a specific type.

For machining and material addition activity – (Activity 4)

In this activity, during some material addition processes, inert gases are used for shielding and for welding purposes, and some tools like welding electrodes are also used. All these are considered under additional process requirements, and these costs fall under the direct cost category since they play a crucial role in the value addition process. The cost of APR (K_{APR}) associated with activity 4 can be calculated by dividing the cost associated with inert gases, welding electrodes, etc., for processing an N_{0i} number of parts of a specific type with Output of stage 2, i.e., N_{0i}.

Therefore, for machining and material addition activity, the total cost of APR (K_{APR}) per part of a specific type can be calculated as

$$\boldsymbol{K_{APR}} = \frac{\boldsymbol{K_{A4}}}{\boldsymbol{N_{0i}}} \qquad \textit{Equation 110}$$

Where:

K_{A4} = cost associated with inert gases, welding electrodes, etc., for processing an N_{0i} number of parts of a specific type.

For assembly activity – (Activity 6)

This activity is similar to the disassembly activity. This activity also considers the cost of fixtures and tools required for assembling the product, and these costs are considered under additional process requirements. The cost of APR (K_{APR}) associated with activity 6 can be calculated by dividing the yearly cost of tools and fixtures (K_{A6}) with the yearly Output of remanufacturing plant.

Therefore, for assembly activity, the total cost of APR (K_{APR}) per product can be calculated as

$$\boldsymbol{K_{APR}} = \frac{\boldsymbol{K_{A6}}}{\boldsymbol{N.n}} \qquad \textit{Equation 111}$$

Where:

K_{A6} = Yearly cost associated with tools and fixtures involved in assembly activity.

For functional testing activity – (Activity 7)

In this activity, the assembled product is subjected to all the tests that a new product has been through to make sure that the remanufactured product is ready for real-life operations. for example, while testing the engine, it has to be filled with supplements like fuel, coolants, lubricating oil, etc. All these kinds of supplements are involved in testing various kinds of products, and this kind of supplement can be considered as additional process requirements which fall under the indirect cost category. The cost of APR (K_{APR}) associated with activity 7 can be calculated by dividing the cost of supplements for processing a batch of size N with the Output of remanufacturing plant, i.e., N.

Therefore, for functional testing activity, the total cost of APR (K_{APR}) per product can be calculated as

$$\boldsymbol{K_{APR} = \frac{K_{A7}}{N}} \qquad \textit{Equation 112}$$

Where:

K_{A7} = cost of supplements for processing a batch of size N.

For painting activity – (Activity 8)

Generally, in this activity, the parts or the products are applied with new paint or surface coatings or protective layers to protect them from the external environment. The painting equipment requires additional supplements like coolants, cleaning medium to clean the equipment before changing to another colour, etc. All these additional supplements are considered under additional process requirements. The cost associated with these additional process requirements can be calculated by dividing the cost of additional supplements for processing a batch of size N with the Output of remanufacturing plant, i.e., N.

Therefore, for painting activity, the total cost of APR (K_{APR}) per product can be calculated as

$$\boldsymbol{K_{APR} = \frac{K_{A8}}{N}} \qquad \textit{Equation 113}$$

Where:
K_{A8} = cost of additional supplements for processing a batch of size N.

As mentioned in section 4.2, along with the direct and indirect costs mentioned in Table 3: Various costs associated with remanufacturing., there are some hidden indirect costs in the remanufacturing process that have to be taken into consideration. In every activity, there might be chances of the presence of some hidden costs. For example, local storage cost associated with machining and material addition activity, safety equipment involved in multiple activities. The hidden costs associated with every activity can be considered under additional costs. The additional cost per product can be calculated by dividing the yearly indirect costs associated with every activity by the yearly Output of remanufacturing plant.
Therefore, the additional cost per product can be calculated as

$$\boldsymbol{K_{Additional}} = \frac{\sum_{i=1}^{8} \boldsymbol{K_{IDC}}}{\boldsymbol{N.n}} \qquad \textit{Equation 114}$$

Where:
K_{IDC} = Yearly indirect costs associated with a particular activity.

Therefore, these are the equations for calculating the various direct, indirect, and hidden costs involved in the whole remanufacturing process. From section 5.2.1 to 5.2.8, cost equations are presented for calculating the cost of a particular resource associated with a specific activity. But the aim of this thesis is to develop a model for calculating the total cost of remanufacturing per product. In the following section, two different models for calculating the total cost of remanufacturing per product are explained in detail.

5.2.9. Cost equations for calculating the total cost of remanufacturing per product

As mentioned in section 2.5, the developed economic model or the cost equation for calculating the cost of remanufacturing per product is based on the activity-based costing (ABC) model and the basic economic model for judging production development. Similar to the ABC model, the developed economic model initially identified the major activities involved in the remanufacturing process (section 4.2), then identified the resources (Table 3) consumed by the activities, and then appropriate cost drivers are chosen as explained in section Cost Drivers. Later, as explained in the basic economic model for judging production development, the direct and indirect costs associated with the resources are coupled with performance factors, as mentioned in section 5.2. Finally, the cost associated with all the activities involved in the recycling process is added up to determine the cost of remanufacturing per product.

Therefore, the cost of remanufacturing per product ($K_{Remanufacturing}$) is calculated as

$$\boldsymbol{K_{Remanufacturing} = K_1 + \sum_{i=1}^{Z} K_2 + K_3 + K_{Material\ Handling} + K_{Storage} + K_{Additional}} \qquad \textit{Equation 115}$$

Where:
K_1 represents the cost associated with stage 1.
K_2 represents the cost associated with stage 2 for a specific part type.
K_3 represents the cost associated with stage 3.

1. **Cost associated with stage 1 –**

As we know that in stage 1, only disassembly activity is included. The cost associated with stage 1 is the cost associated with the disassembly activity, and it can be calculated as

$$K_1 = K_{Disassembly} \qquad \textit{Equation 116}$$

$$K_{Disassembly} = K_{Old} + K_{Personnel} + K_{APR} \qquad \textit{Equation 117}$$

Therefore,

$$\boldsymbol{K_1} = \frac{\sum_{i=1}^{N} K_M}{N} + \frac{K_D .\ N_{OP}}{N}\left(\frac{t_0 .\ N}{(1-q_p).\ (1-q_s)} + T_{su}\right) + \frac{K_{A1}}{N.n} \qquad \textit{Equation 118}$$

2. **Cost associated with stage 2 –**

As mentioned in section 4.1, Cleaning activity, Inspection 1, machining, and material addition, and inspection 2 are included in stage 2. The cost associated with stage 2 can be calculated by adding the costs associated with cleaning, inspection 1, machining and material addition, and inspection 2 activities.

The cost for processing a specific part in stage 2 can be calculated as

$$K_2 = ((N_{sp})\ (K_{Cleaning} + K_{Inspection1}) + ((N_{Reman})\ (K_{MM} + K_{Inspection2})) + ((N_{New/Used})\ *(K_{New/used})) \qquad \textit{Equation 119}$$

And the cost for processing a product in stage 2 can be calculated as

$$\sum_{i=1}^{Z} \boldsymbol{K_2} = \sum_{i=1}^{Z}(N_{SP})\left(K_{Cleaning} + K_{inspection\ 1}\right) + (N_{Reman})\big(K_{MM} + K_{inspection\ 2}\big) + \big(N_{New/Used}\big)\big(K_{New/used}\big) \qquad \textit{Equation 120}$$

Where:
Z = Total number of various parts involved in a product.

- So, the cost for processing a part in **cleaning activity** can be calculated as

$$\mathbf{K_{Cleaning} = K_{Equipment} + K_{Personnel} + K_{APR}}$$

Therefore,

$$\boldsymbol{K_{Cleaning}} = \left(\frac{K_{CP}}{N_{0i}}\left(\frac{t_0 \cdot N_i}{(1-q_p)}\right) + \frac{K_{CS}}{N_{0i}}\left(\frac{t_0 \cdot N_i}{(1-q_p)} \cdot \frac{q_s}{(1-q_s)} + T_{su}\right)\right) + \left(\frac{K_D \cdot N_{OP}}{N_{0i}}\left(\frac{t_0 \cdot N_i}{(1-q_p) \cdot (1-q_s)} + T_{su}\right)\right) + \frac{K_{A2}}{N_{0i}}$$

Equation 121

- The cost for processing a part in **inspection 1 activity** can be calculated as

$K_{Inspection\ 1} = K_{Equipment} + K_{Personnel}$ *Equation 122*

Therefore,

$$\boldsymbol{K_{Inspection\ 1}} = \left(\frac{K_{CP}}{N_{0i}}\left(\frac{t_0 \cdot N_i}{(1-q_p)}\right) + \frac{K_{CS}}{N_{0i}}\left(\frac{t_0 \cdot N_i}{(1-q_p)} \cdot \frac{q_s}{(1-q_s)} + T_{su}\right)\right) + \left(\frac{K_D \cdot N_{OP}}{N_{0i}}\left(\frac{t_0 \cdot N_i}{(1-q_p) \cdot (1-q_s)} + T_{su}\right)\right)$$

Equation 123

- The cost for processing a part in **machining and material addition activity** can be calculated as

$K_{MM} = K_{materail} + K_{Tool} + K_{Equipment} + K_{Personnel} + K_{APR}$ *Equation 124*

Therefore,

$$\boldsymbol{K_{MM}} = \frac{K_B}{N_{0i}} + \frac{K_T}{N_{Oi}} + \left(\frac{K_{CP}}{N_{0i}}\left(\frac{t_0 \cdot N_{0i}}{(1-q_p)}\right) + \frac{K_{CS}}{N_{0i}}\left(\frac{t_0 \cdot N_{0i}}{(1-q_p)} \cdot \frac{q_s}{(1-q_s)} + T_{su}\right)\right) + \left(\frac{K_D \cdot N_{OP}}{N_{0i}}\left(\frac{t_0 \cdot N_{0i}}{(1-q_p) \cdot (1-q_s)} + T_{su}\right)\right) + \frac{K_{A4}}{N_{0i}}$$

Equation 125

- The cost for processing a part **in inspection 2 activity** can be calculated as

$K_{Inspection\ 2} = K_{Equipment} + K_{Personnel}$ *Equation 126*

Therefore,

$$\boldsymbol{K_{Inspection\ 2}} = \left(\frac{K_{CP}}{N_{0i}}\left(\frac{t_0 \cdot N_{0i}}{(1-q_p)}\right) + \frac{K_{CS}}{N_{0i}}\left(\frac{t_0 . N_{0i}}{(1-q_p)} \cdot \frac{q_s}{(1-q_s)} + T_{su}\right)\right) + \left(\frac{K_D \cdot N_{OP}}{N_{0i}}\left(\frac{t_0 \cdot N_{0i}}{(1-q_p) \cdot (1-q_s)} + T_{su}\right)\right)$$

Equation 127

3. Cost associated with stage 3 –

As mentioned in section 4.2, assembly activity, functional testing activity, and painting activity are included in stage 3. So, the cost associated with stage 3 can be calculated by adding the costs associated with assembly, functional testing, and painting activities.

Therefore, the cost for processing a product in stage 3 can be calculated as

$K_3 = K_{assembly} + K_{Func.Testing} + K_{Painting}$ *Equation 128*

- The cost for processing a product in **assembly activity** can be calculated as

$K_{Assembly} = K_{Personnel} + K_{APR}$ *Equation 129*

Therefore,

$$\boldsymbol{K_{Assembly}} = \frac{K_D \cdot N_{OP}}{N}\left(\frac{t_0 \cdot N}{(1-q_p) \cdot (1-q_s)} + T_{su}\right) + \frac{K_{A6}}{N . n}$$

Equation 130

- The cost for processing a product in **functional testing activity** can be calculated as

$K_{Func.\ Testing} = K_{Equipment} + K_{Personnel} + K_{APR}$ *Equation 131*

Therefore,

$$K_{Func.Testing} = \left(\frac{K_{CP}}{N}\left(\frac{t_0 \cdot N}{(1-q_p)}\right) + \frac{K_{CS}}{N}\left(\frac{t_0 \cdot N}{(1-q_p)} \cdot \frac{q_s}{(1-q_s)} + T_{su}\right)\right) + \left(\frac{K_D \cdot N_{OP}}{N}\left(\frac{t_0 \cdot N}{(1-q_p) \cdot (1-q_s)} + T_{su}\right)\right) + \frac{K_{A7}}{N}$$

Equation 132

- Similarly, the cost for processing a product in **painting activity** can be calculated as

$K_{Painting} = K_{paint/coating} + K_{Equipment} + K_{Personnel} + K_{APR}$ *Equation 133*

Therefore,

$$K_{painting} = \frac{K_p}{N} + \left(\frac{K_{CP}}{N}\left(\frac{t_0 \cdot N}{(1-q_p)}\right) + \frac{K_{CS}}{N}\left(\frac{t_0 \cdot N}{(1-q_p)} \cdot \frac{q_s}{(1-q_s)} + T_{su}\right)\right) + \left(\frac{K_D \cdot N_{OP}}{N}\left(\frac{t_0 \cdot N}{(1-q_p) \cdot (1-q_s)} + T_{su}\right)\right) + \frac{K_{A8}}{N}$$

Equation 134

4. Cost associated with material handling –

The costs associated with material handling can be calculated as

$$K_{Material\ Handling} = \frac{a_f \cdot K_0 (1 + K_0 \cdot N_{ren}) + K_{MH} + K_{fuel} + Y.K_{Area} + K_D.N_{OP}.T_{Plan}}{N.n}$$

Equation 135

5. Cost associated with storage –

The cost associated with storage can be calculated as the sum of the storage cost associated with products and the storage costs associated with spare parts of various types (i = 1…...Z).

Therefore, the storage cost per product can be calculated as

$$K_{Storage} = \left(\left(\frac{Y_N . K_{Area} + K_{s.equip(N).}}{(365)\,.(24)} \right) . \left(\frac{t_{avg(N)}}{N} \right) \right) + \sum_{i=1}^{Z} (N_{New/Used}) \cdot \left(\frac{Y_{N_p} . K_{Area} + K_{s.equip(N_p)}}{(365)\,.(24)} \right) . \left(\frac{t_{avg(N_p)}}{N_p} \right) \qquad \textit{Equation 136}$$

6. Costs considered under additional costs –

The costs that fall under additional costs can be calculated as

$$K_{Additional} = \frac{\sum_{i=1}^{8} K_{IDC}}{N.n} \qquad \textit{Equation 137}$$

From the above equation, we can calculate the cost of remanufacturing per product by calculating the costs associated with every activity involved in remanufacturing. If one would like to know about the costs associated with a particular resource group (like the total cost of materials or the total cost of the equipment involved in remanufacturing plant etc.), then the total cost of remanufacturing per product can be calculated by using the following equation.

$$K_{Remanufacturing} = K_{Materials} + K_{Tools} + K_{Equipment} + K_{Personnel} + K_{Additional} + K_{material\ handling} + K_{Storage} + K_{APR.} \qquad \textit{Equation 138}$$

Where:

$K_{Materials}$ represent the cost associated with used products, the material used in machining and material addition activity, paints, and other protective coatings used in the painting activity.

K_{Tools} represents the cost associated with machining tools used in machining and material addition activity.

$K_{Equipment}$ represents the cost associated with all the processing equipment involved in all the activities.

$K_{Personnel}$ represents the cost associated with all the personnel involved in all the major activities. Personnel cost associated with material handling is excluded.

$K_{\text{Material handling}}$ represents the cost associated with material handling systems involved in between all the activities and in between the various activities and storage.
K_{APR} represents the cost associated with additional process requirements involved in activities 1, 2, 4, 6, 7, and 8.
K_{Storage} represents the storage cost associated with products and spare parts of various types.
$K_{\text{Additional}}$ represents the activity-based indirect costs.

As mentioned in table 4, every resource group contains various resources. The cost associated with each resource group can be calculated by adding the cost of various resources involved in each group, and while adding up the cost of various resources, it is necessary to make sure that every resource has the same unit, i.e., cost per product.

These are the two models for calculating the cost of remanufacturing per product. In fact, both the models give the same cost for remanufacturing a product but choosing an appropriate model depends upon the type of study and type of results required. For example, suppose a remanufacturing industry would like to analyze the total annual cost associated with the equipment. In that case, it can choose the model which was built by considering resource groups. Similarly, suppose a remanufacturing industry would like to analyse the cost associated with the functional testing activity. In that case, the industry can choose the model which was built by considering activities.

6. Discussions

This chapter discusses the identified gaps in the literature survey, the advantages and limitations of the developed models for recycling and remanufacturing, and the flexibility of the models to adopt various materials, processes, and various production scenarios.

6.1. Identified gaps in the literature review.

1. While calculating the cost of recycling, it is important to consider all the resources associated with various activities of recycling. Before looking into the cost, it is quite important to understand the various activities and their associated resources in the recycling process. In the literature, (Reck & Graedel, 2012) discussed three major stages involved in recycling: collection, pre-processing, and end processing. They mentioned collecting, sorting, pre-treatment, and processing material in the furnace in these three stages. (Shemi, et al., 2018) discussed the various recycling methods, scrap conversion, and chemical reagents used in the recycling process. But they haven't discussed anything about the various stages involved in the recycling process. Graeme Hoyle discussed the dismantling of complex products, separating reused materials, further sorting materials, and melting scrap. (Matsumoto & Komatsu, 2015) discussed dust, slag, sludge, hazardous waste, and various other wastes generated during steel recycling. To explain the waste in detail, they have mentioned shredding, sorting, and processing activities. (Wright, et al., 2002) discussed various kinds of solid waste, waste treatment before disposal, and the disposal cost. (Furberg, et al., 2019) discussed various chemical reagents and various kinds of solid waste generated in recycling. (Hu, et al., 2002) discussed the reverse logistics system for treating hazardous waste. Similarly, as mentioned in the literature review (Chapter 2.5), several authors discussed specific topics in detail or discussed very few topics in general. But none of them explained in detail all the major activities and their associated resources involved in recycling.

2. When it comes to the cost models for calculating the cost of recycling, there are very few models mentioned in the literature. Ewa Dostatni, Anna Karwasz, and Jacek Diakun have developed a model for calculating the cost of recycling at the design phase. This model has only considered three different costs – Disassembly cost, recycling cost, and disposal cost. Out of these three costs, they have mentioned in detail various factors that have to be taken into consideration while calculating the disassembly cost. But they haven't discussed anything about the calculation of recycling and disposal costs. Bas Wouterszoon Jansen, Anne van Stijn, Vincent Gruis, Gerard van Bortel (2020) developed a life cycle costing model. In that model, they explained the cost of reusing, recycling, and remanufacturing. Under recycling costs, they have considered transportation cost, waste disposal cost, processing (recycling) cost, and the amount of recyclable material. Similarly, (Jawahir & Bradley, 2016) developed a total life cycle costing model. In that model explained the cost of reusing, recycling, and remanufacturing. The recycling process has considered the cost associated with material processing, energy cost, transportation cost, labour cost, and waste management cost. From the literature survey, we found these existing models for calculating the cost of recycling. **But the major issue is every model has explained the various costs associated with recycling. Still, none of them explained anything in detail about calculating these costs and the factors that have to be considered while calculating these costs.** (Spoel, 1990) mentioned that every year millions of tons of metals are being recycled around the world. Even more, can be done if proper economic models and incentives are present for recycling.

3. When it comes to remanufacturing, (Andrew Munot, et al., 2015) have discussed five major activities involved in remanufacturing – Inspection, disassembly, reprocessing, reassembly, and testing. Also, for every activity, they gave a brief description of the various operations and the resources required in every activity—similarly, (Kin, et al., 2014) have discussed the various reconditioning operations based on the inspection results, and they also discussed multiple resources associated with multiple reconditioning

operations. (Jiang, et al., 2016) have discussed various cleaning technologies and cleaning mediums used in cleaning activity plays a crucial role in remanufacturing and for every cleaning technology they mentioned about required resources as well. **Even though many researchers have described the remanufacturing process well, none have considered the total cost of remanufacturing**.

4. In recycling and remanufacturing, the most important common gap is the lack of proper economic models for calculating the cost of recycling and remanufacturing. To fill this gap, we have developed economic models to calculate the cost of recycling per ton and cost of remanufacturing per product. These models are developed based on the activity-based costing (ABC) model and basic economic model for judging production development as explained in chapter 5.

6.2. Advantages of the developed models

1. In section 5.1.8, two different models are presented for calculating the cost of recycling per ton of material. In section 5.2.9, two different models are presented for calculating the cost of remanufacturing a product. These two different models in each section give the same cost for recycling a ton of material and remanufacturing a product, but each model has its respective advantages.

   - Out of the two models, one model calculates the cost of recycling or remanufacturing **by considering activities**.
   - $\mathbf{K_{Recycling} = K_{Collection\ and\ Storing} + K_{Disassembly} + K_{Shredding\ and\ Sorting} + K_{Pre\text{-}treatment\ and\ Processing} + K_{waste\ Management}}$

- By using this model, along with the cost of recycling or remanufacturing,
    - The cost associated with every activity (Figure **26**) involved in either recycling or remanufacturing process can be monitored.
    - The percentage of a particular activity's cost in the total cost of recycling or remanufacturing (Figure **27**) can be observed.
    - And the variations in the various activity costs due to change in various factors during production development can be monitored.

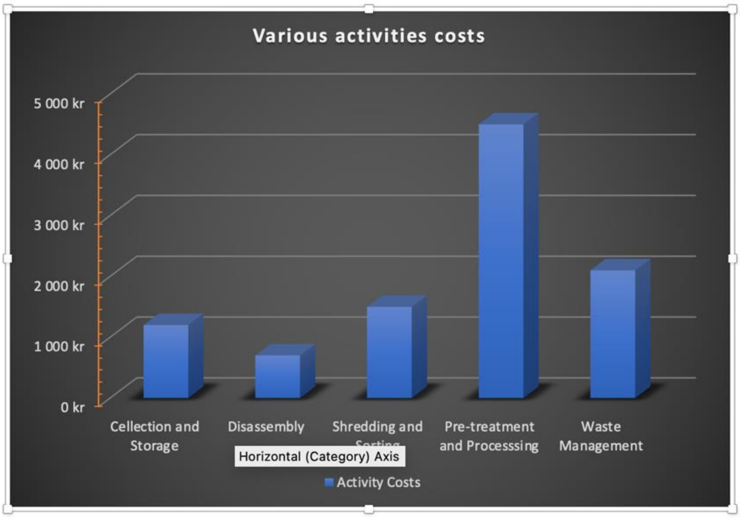


Figure 26: Costs associated with various activities in the recycling process

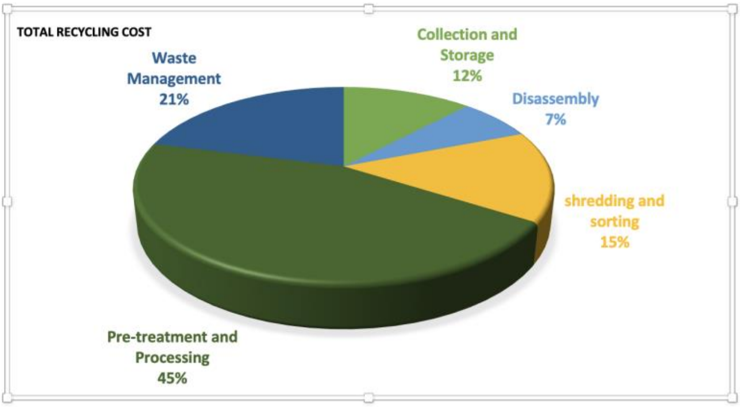


Figure 27: Percentage of each activity cost in the total cost of recycling.

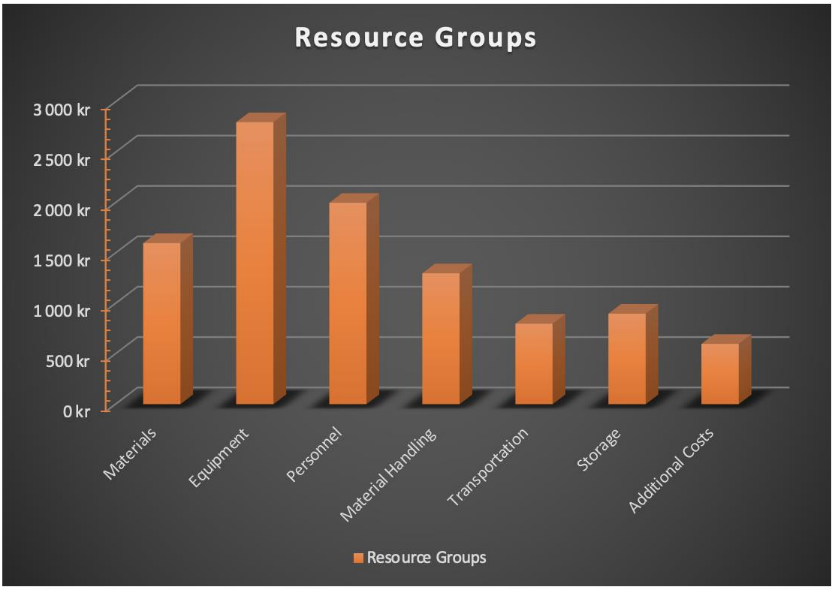


Figure 28: Costs associated with various resource groups in the recycling process

- Similarly, the other model also calculates the cost of recycling or remanufacturing but **by considering resource groups**.

$$K_{Recycling} = K_{Materials} + K_{Equipment} + K_{Personnel} + K_{material\ handling} + K_{Transportation} + K_{Storage} + K_{Additional}$$

By using this model, along with the cost of recycling or remanufacturing:

- The cost associated with every resource group Figure **28** involved in either recycling or remanufacturing process can be monitored.
- The percentage of a particular resource group's cost in the total cost of recycling or remanufacturing can be observed in the Figure 29.
- And the variations in the various resource group costs due to change in various factors during production development can be monitored.

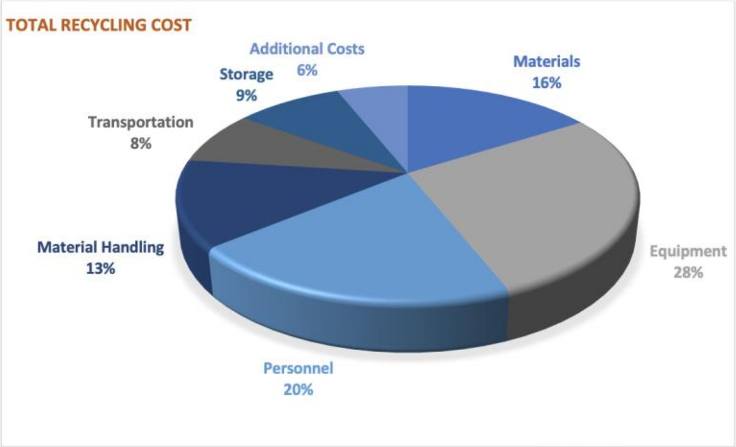


Figure 29: *Percentage of each resource group's cost in the total cost of recycling.*

2. As seen in the basic model for judging production development, in both the developed models (for calculating recycling cost and remanufacturing cost), the factors that affect the performance are considered in every activity. With this consideration, there are few advantages. They are –

a. **The consideration of performance factors in every activity helps monitor the ongoing production to identify the areas that need improvement.**
b. **This consideration also forms a basis for the decision-making during the process or product development in the identified areas.**
    - From the equations mentioned in sections 3.4 and 4.3, we can see that a small change in a particular performance factor will affect the other performance factors, which are either directly or indirectly related to it. For example, a change in downtime losses changes the actual processing time of a batch (Figure 30).
    - Similarly, from the equations mentioned in sections 5.1 and 5.2, we can see that a change in performance factors will affect the cost associated with a particular activity, cost associated with a particular resource group, and the total cost of recycling remanufacturing. For example, a change in downtime losses changes the actual processing time of a batch, which changes the processing cost (Figure 29).
    - Generally, during the product development, a few parameters or factors will be altered for improving the production performance (for example, minimizing the downtime and increasing batch size to reduce the part cost.). This model helps in studying the influence of a factor(s) on the other factor(s), as shown in figures 32,33,34 and 35. In this way, this model forms a basis for decision-making during product development.

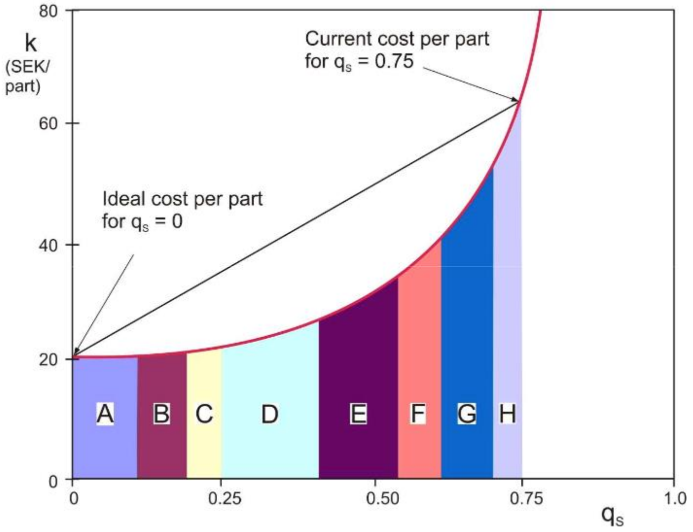


Figure 30: *Example for the influence of the downtime on the processing cost of a part in the machining activity of a remanufacturing facility* ***(Ståhl, et al., 2007).***

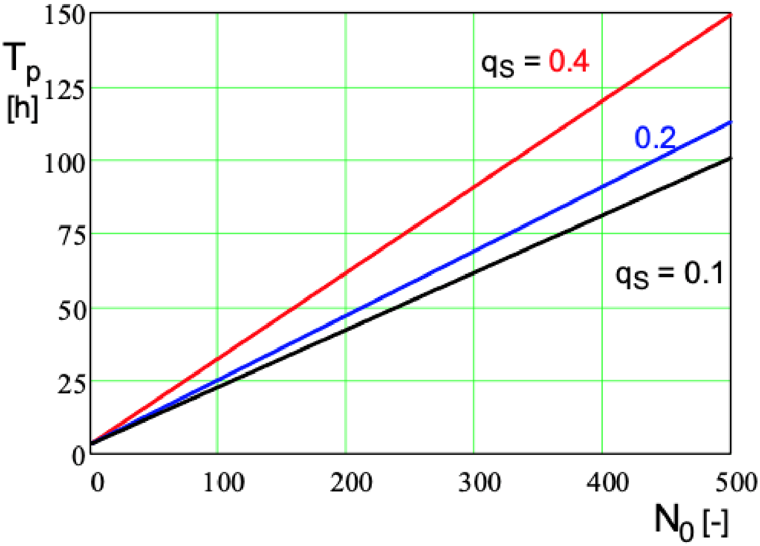


Figure 31: Example for the influence of downtime and batch size on the actual processing time of a part ***(Ståhl, et al., 2007)****.*

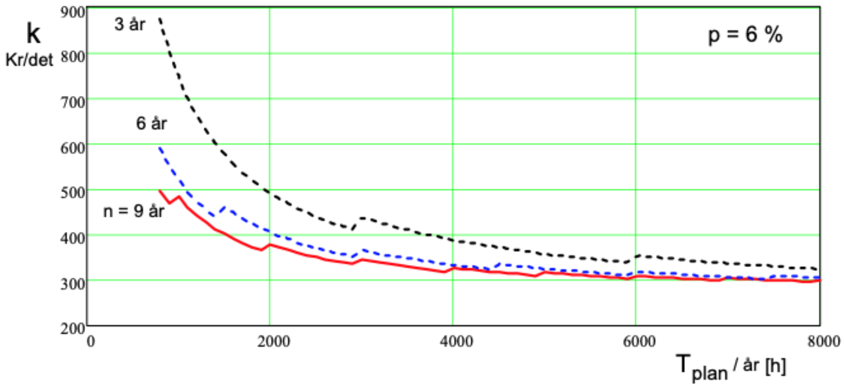


Figure 32: *Example for the influence of planned production time and number of years of use of equipment on the processing cost of a part in the machining activity of a remanufacturing process* ***(Ståhl, et al., 2007)****.*

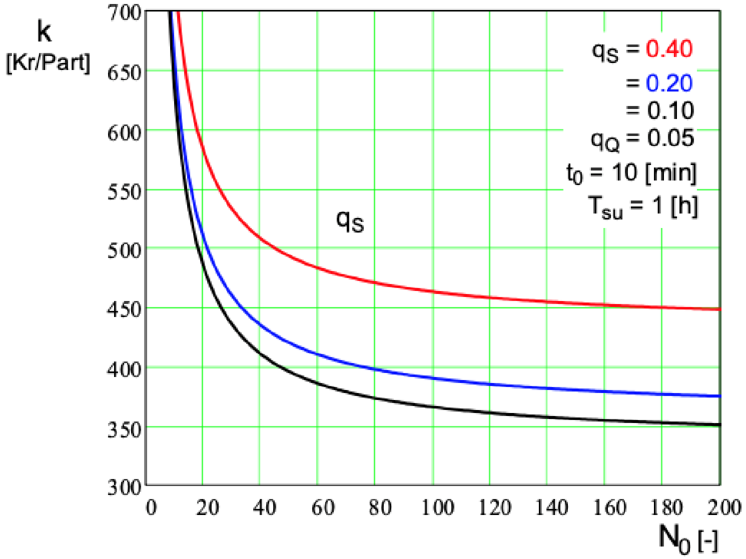


Figure 33: *Example influence of downtime and batch size on the processing cost of a part in the machining activity of a remanufacturing process* ***(Ståhl, et al., 2007)****.*

c. After identifying the area that needs improvement, to choose the development strategy, it is quite important to identify the various aspects that affect the performance. These developed models also help implement various tools like Five why Pareto and Ishikawa charts to identify the various factors and how they are affecting the performance.

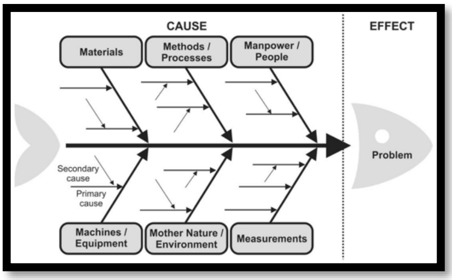


Figure 34: *Ishikawa Chart* ***(Hristoski, 2017)***.

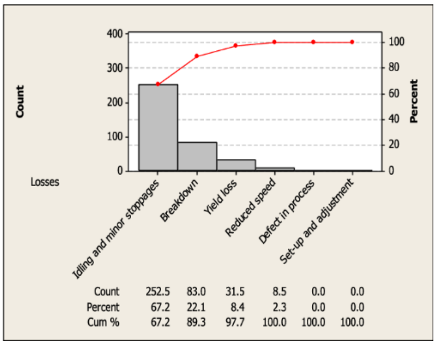


Figure 35: *Pareto diagram representing major losses in a processing step* ***(Rimantho, 2017)***.

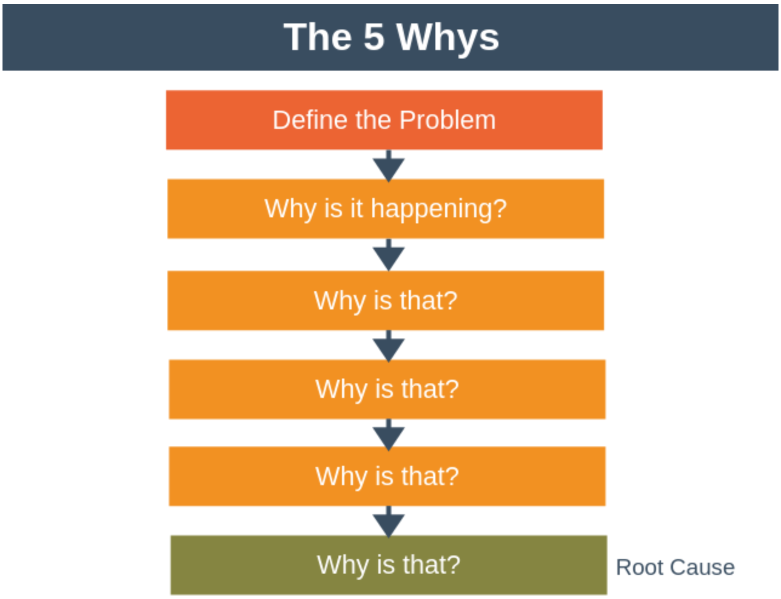


Figure 36: *Five why methodology* **(programmanagement, u.d.)**.

3. In contrast to the various models found in the literature review, the developed model for calculating the cost of recycling considers various direct costs, indirect costs, and also the costs related to the environment (waste treatment and disposal cost), which helps in calculating the cost of recycling more accurately.
4. The model developed for the recycling process also considers the cost associated with various kinds of material losses involved in various activities by considering x_{in} and x_{out} in every activity. Similarly, the model for remanufacturing also considers the cost associated with rejected parts and new parts added to the product. These considerations make these models even more precise.
5. In general, the cost of personnel depends upon various factors like experience, skills, area of expertise, designation, etc. In recycling and remanufacturing processes, various personnel with the various skill set in various activities are required. To provide more accurate results, these models have considered the cost of personnel associated with each activity. This consideration also helps in

studying the influence of personnel cost on the total cost of recycling or remanufacturing during the automation of a particular activity.

6. Energy consumption is one of the primary factors that have to be considered in recycling and remanufacturing processes. In both these models, the cost associated with energy consumed by the processing equipment (Involved in all activities), material handling equipment, and the transporting equipment (fuel) has been considered. This consideration helps in monitoring the consumption of energy by each piece of equipment. Also, it helps in decision-making while shifting towards renewable energies (For example, solar power, electric trucks, etc.).
7. During the life cycle assessment (LCA) of the product, it is important to consider the cost associated with recycling and remanufacturing. These developed models for recycling and remanufacturing helps in identifying the major factors that have to be considered while calculating the cost associated with recycling and remanufacturing during LCA.

Along with all these advantages, there are few more advantages with these developed models. But it is appropriate to discuss them under the flexibility section since these advantages make the developed models more flexible to adopt the various changes as discussed in the following section (6.3).

6.3. Flexibility of the developed models

Model for calculating the cost of recycling –

1. The model for calculating the cost of recycling is designed to be used for various types of scrap. Generally, the collected scrap can be complex products like automobiles, refrigerators, or it can also be a high-value scrap from the machining operations in a manufacturing industry. As mentioned in section 5.1.3, if the collected scrap is mixed scrap or complex products, then x_1, x_2, x_3 have to be considered. Suppose the collected scrap is a high-value scrap from machining operations in the manufacturing industry. In that case, $x_2=$

x_3=0 since the scrap generated from the machining process contains only a desired recyclable material.

2. Based on the type of scrap, the disassembly activity and the shredding process can be chosen. For example, if the collected scrap is complex products, the then products need to be disassembled first, and then they should be shredded into pieces. But suppose the collected scrap is high-value scrap from machining operations in the manufacturing industry. In that case, disassembly activity and the shredding process can be avoided since the scrap generated from machining operations will be in the form of chips that requires neither disassembly nor shredding.
3. The pre-treatment process considered in the model helps in adopting the model for various metals. Because, in the pre-treatment process, either the recyclable material is cleaned to make it free from contaminants like oils, grease, etc. The recyclable material is converted into intermediate compounds to get the desired Output. For example, the steel scrap generated by machining operations might get contaminated with coolants. It should be cleaned before melting it in the furnace. Similarly, in the indirect recycling process of WC, nitrate salts are used for converting WC scrap into sodium tungstate from which tungsten will be extracted during pre-treatment.
4. The recycling efficiency considered in pre-treatment and processing activity helps in using the model for various metals. Because various metals will have various recycling efficiencies and, in this model, the recycling efficiency is coupled with the Output of the recycling facility. Change in recycling efficiency will affect the Output of the recycling facility. We know that the Output of the recycling facility plays a crucial role in the cost of recycling.
5. In the recycling process, various kinds of reagents are required for processing scrap in various stages. For example, reagents are required in pre-treatment and processing activity for processing scrap, and also some other reagents are required for processing waste in waste management activity. All these reagents involved in various activities are considered additional process requirements in

the respective activity. This consideration makes the equation more flexible to adapt for various metals since various metals require various kinds of reagents in various activities.

6. Also, the developed model considers direct costs, indirect costs, and the costs related to the environment (waste treatment and disposal cost), as mentioned in Table 1.

All these advantages make the model more flexible and make it more feasible to adopt it by various recycling systems (like in-house recycling system, third-party recyclers, etc.)

Model for calculating the cost of remanufacturing –

1. The developed model for calculating the cost of remanufacturing can be easily adapted to various types of products or parts (like engine, transmission, brake caliper, etc.). Generally, for every product, based on the product size and complexity, the processing time varies. As explained in section Technological or Performance factors considered in Remanufacturing, the processing time of a product in a particular activity is one of the significant factors that affect the remanufacturing cost of a product. In this model, the actual processing time has been considered in every activity, which helps adapt the model for various products or parts.
2. Generally, based on the product's condition, the cost of the used products varies from one product to another product. In this model, the cost of each individual product is taken into account, and then the total cost of all the products was distributed over the batch size so that the average cost of a used product (core) can be achieved. In this way, this model provides the flexibility of taking the cost of individual products into account.
3. The developed model for calculating the cost of remanufacturing can be easily adapted to various products in different conditions (like moderately used products, products with rust, worn-out products, etc.). During remanufacturing, few parts in a product will be replaced with new features, and based on the condition of the

product, the number of new parts used in a product varies from one product to other. In this model, the cost associated with new parts used in a single product has been considered, which helps adapt the model for various products in different conditions.

4. This model provides flexibility in placing the painting activity either before assembly or after assembly, or after functional testing based on its type and application. For example, Mini Cooper is painting its remanufactured engines before assembly, and Caterpillar is painting the engines after functional testing.

In this way, all these advantages make the model more flexible and make it more feasible to adopt it by original equipment manufacturers (OEM's) and contracted (outsourced) remanufacturers

7. Conclusion

In conclusion, this thesis has pursued insight into the current recycling and remanufacturing economic models suited for sustainable product development. It has been found that these industries are gaining traction with an increase in resource consumption and depleting natural resources. Due to the rapid change in industries, new economic models are required to change how the business is being carried out within resource management. Moreover, the reports have suggested that more economical models are required to improve the product and material recovery. Based on the key finding, this thesis has identified the need for economic models:

In addition to the theoretical gap that exists in the cost models from our study, we have identified a fundamental gap between the economic and technological factors in understanding and reintroducing materials into the loop. There is a substantial gap in the literature on the cost model for recycling and remanufacturing. There was often a lack of a well-defined model to analyze and support these businesses promptly. Consequently, many potential opportunities for remanufacturing and recycling are missed. There are very few models that explain the direct costs (transportation, energy, Etc.) associated with the process. More interestingly, none of the models included technological factors or indirect costs. The costing relied on retrospective data to calculate costs with minimalistic consideration of activities. A possible solution is needed to overcome this gap through a systematic approach that structures both the performance and economic factors by identifying the critical parameters at each stage of the respective process.

This thesis demonstrates a developed economy model for recycling and remanufacturing to address the gaps mentioned above, considering the direct and indirect cost to serve as an economic model that drives towards sustainable product development and promotes a circular economy. These models are developed for recovering the materials or products from various types of scrap. Selecting an appropriate EOL option potentially reduces the cost and preserves the values of the material and product. The framework and developed models exemplify the aid to the recyclers and remanufacture in better decision-making using systematic production analysis (SPA) and determine the accountability of each activity and process. These models are more generalized toward metals; however, they can be adapted to different materials due to their flexibility. While addressing these gaps most stressing issues was the lack of a well-defined process for recycling. This model can drive counties' innovations sustainable product development to reduce the production costs and environmental impacts.

7.1. Limitations of the models

1. The annual demand for recycled material or remanufactured products plays a crucial role in selecting the batch size, which affects the cost of recycling and remanufacturing. In most situations, the annual demand is uncertain. These developed models for recycling and remanufacturing haven't considered the uncertainty of demand.
2. The equations for calculating the cost of recycling are developed for metal recycling process.
3. The equation for calculating the cost of remanufacturing is only applicable to original equipment manufacturers (OEM's) and contracted (outsourced) remanufacturers. This model does not apply to local remanufacturers since local re-manufacturers will get used products directly from various customers. So, in order to adopt this equation, the local remanufacturers should add an activity called sorting activity to separate the various kind of products collected from various customers.
4. These developed models contain several numbers of parameters. To get more accurate results, these models demand well-structured data.

7.2. Future scope

1. The model developed for recycling can also be adapted for other materials like glass, plastics, composites, etc., by adding appropriate activities and resources to recycle those materials.
2. Similarly, the model developed for remanufacturing can also be adopted by local remanufacturers by adding sorting activities to separate the products from various manufacturers.

3. The models developed for recycling and remanufacturing can also be adopted for price quoting purposes by adding a profit margin parameter.
4. In the developed models, we can see several factors or parameters that play a crucial role in determining a particular result (like calculating the cost of a resource or an activity, the total cost of recycling, processing a batch in an activity, etc.). In future studies, statistical analysis of data can be employed to identify the various factors and their influence on a particular result, forming a basis for decision-making and optimizing the existing process.
5. The major limitation of these models is that they demand well-structured data for every input. But in many cases, the available amount of data is minimal, and in some cases, several inputs are uncertain. In future studies, to solve these cases, a dynamic simulation can be adopted. In this dynamic simulation, the variables and the parameters are defined in terms of statical distributions. These statistical distributions contribute as an input to the analysis. Also, in future studies, adopting appropriate statistical distribution functions for performing dynamic simulation can be studied.

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