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Enhancing Product Design for Disassembly: A Study Utilizing Computer Aided Design (CAD) Software and the DeSE Tool

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Table of Contents

LIST OF FIGURE

LIST OF TABLE

ABSTRACT

This study investigates the disassembly complexity, environmental impact, and recyclability of a speed reducer gearbox and a gas knob assembly, utilizing DeSE software to quantify disassembly effort and identify design inefficiencies. The analysis identifies that the gearbox have high disassembly complexity (*Icom*), predominantly in terms of shaft, key and gear interference fits and an excessive use of fasteners, and in contrast, a relatively low disassembly complexity for the gas knob, therefore, it is easier to maintain.

To address these issues, a redesign strategy was implemented. The gearbox redesign replaced interference fits with spline connections and reduced sub assembly of main gear box housing and hexagonal shaped housing with ribs fasteners by 50%, leading to a 32% reduction in disassembly complexity. The gas knob redesign focused on optimizing connections and reducing the number of fasteners, resulting in a slight improvement in ease of disassembly. Environmental impact analysis showed that the gearbox's primary emissions stemmed from its energy-intensive use phase (99.96% of total CO_2 emissions), while the gas knob's impact was initiated by material extraction and manufacturing. Both products demonstrated high recyclability potential, with Recyclability Indices (Rcyc) of 0.85 for the gearbox and 0.84 for the gas knob.

Key challenges encountered included difficulty in physically disassembling the gearbox due to the need for a hydraulic press, limited literature on disassembly complexity indices (*Icom, C'r, C'h*), generalization of material composition, and the learning curve of Solid Edge CAD (Computer Aided Design) software. Despite these obstacles, the study successfully demonstrated how Design for Disassembly (DfD) and Design for Recycling (DfR) principles can enhance ease of maintenance, reduce environmental impact, and improve recyclability. The findings provide a valuable framework for future engineering design, reinforcing the importance of sustainability, efficiency, and circular economy principles in mechanical product development.

Keywords: *Disassembly Complexity(Icom), Design for Disassembly (DfD), Design for Recycling (DfR), Design for Sustainability and Environment (DeSE), Interference Fit, Recyclability Index, Environmental Impact, Circular Economy, Life Cycle Assessment (LCA), Sustainability in Engineering.*

ACRONYMS LIST

CAD – Computer-Aided Design

C'h – Average Handling Complexity Index

C'r – Average Removal Complexity Factor

DfD – Design for Disassembly

DfR – Design for Recycling

DeSE – Design for Sustainability and Environment

GHG – Greenhouse Gas

Icom – Overall Disassembly Complexity Index

LCA – Life Cycle Assessment

RBRn – Recyclability Benefit Ratio

Rcyc – Overall Recyclability Index

CO_2 eq – Carbon Dioxide Equivalent

Kg CO_2 eq- Kilograms of CO_2 Equivalent

Kg CFC11 eq- Kilograms of CFC-11 Equivalent

Kg Sb eq- Kilograms of Antimony Equivalent

M^2a- Square Meters

Kg PO_4 eq- Kilograms of Phosphate Equivalent

EOL- End-of-Life

GHG- Green House Gas

PART ONE- INTRODUCTION

1.1 Background of the study

Increased demand for green product design has generated increased focus on environmentally sound strategies, such as eco-design and Design for Disassembly (DfD). Both of these strategies aim to minimize environmental impact throughout the whole life cycle of a product, from production to recycling or disposal, by focusing on resource efficiency, recyclability, and ease of maintenance. While sectors shift to circular economy models, mechanical parts like the speed reducer gearbox and gas knob (gate valve) have specific challenges and potentialities for improving sustainability.

Mechanical assemblies commonly face design challenges hindering disassembly processes. Characteristics including interdependent parts, use of varied materials, and reliance on non-removable fasteners reduce the labor intensity, cost, and environmental requirements of maintenance and end-of-life recycling processes. This calls for the implementation of a systematic method in product redesign using advanced tools and quantitative methods to enhance disassembly processes without compromising product functionality.

In this study, the redesign of a gas knob and speed reducer gearbox by DfD is considered. Both systems are examples of common disassembly challenges: the gas knob, with its complicated design and composite materials, makes recycling awkward, while the gearbox, with its strong and tight-fitting construction, necessitates enormous effort to maintain and disassemble. Using disassembly complexity measures and software like DeSE, this study will determine and reduce effort-intensive components to enable more efficient and sustainable designs.

This research combines quantitative measures with qualitative findings to develop practical solutions for reducing disassembly effort, enhancing recyclability, and reducing costs at end-of-life. By bridging critical knowledge gaps in DfD principle application, this research contributes to the extensive corpus of sustainable mechanical design research, offering practical recommendations to guide further innovations in green design practices.

1.2 Problem Statement

With an increased focus on sustainability in engineering, we need products that are designed with disassembly and recycling in mind. Recognizing these challenges, DfD has developed as an important approach in creating designs that can easily and efficiently be maintained, repaired and recycled at the end of their life. Nonetheless, every used part presents challenges when today's mechanical design practices fail to consider DfD principles, resulting in added complexity, cost, and detrimental effects on the environment. We can see such deficiencies in components like gas knobs and speed reducer gearboxes.

Research shows that 30% of production downtimes are due to inefficient equipment maintenance, costing operations an estimated $222 billion annually in the U.S. alone (Deloitte, 2024). For example, repairing or replacing components in a gearbox can require an excessive amount of time and the use of specialized tools that may rarely be utilized again. This not only reduces productivity but also increases operational costs.

Mechanical assemblies that do not integrate DfD often face significant maintenance challenges. Unplanned downtime in manufacturing can cost companies as much as $260,000 per hour (IIoT World, 2017). Additionally, 82% of companies have reported experiencing unplanned downtime over a three-year period, underscoring how widespread maintenance-related issues are (IIoT World, 2017). These challenges highlight the importance of adopting DfD principles to improve maintenance efficiency, reduce efforts during maintenance, and lower operational costs.

Economic and environmental challenges are closely correlated with design decisions. According to a research, 70% of the lifecycle costs are defined during the design phase (Pahl, G., & Beitz, W., 2007). Optimized parts with arbitrary fastener usage, mixed materials and complexity increase disassembly effort and lead to preventable difficulties in recycling. Low resource recovery rates also result in higher wastage of materials and greenhouse gas emissions. One such approach is to improve disassembly efficiency which has been shown to increase recycling rates by as much as 50%, thus reducing impact on the environment.

The complex structure of the gas knob, constructed with multiple small components and mixed materials like plastics and metals, poses challenges for maintaining and recycling it. Likewise, the speed reducer gearbox's purposefully rugged and closely coupled construct involves high interference fits and many fasteners, so disassembly is thus labor- and cost-intensive and results in high effort.

The absence of DfD principles in these designs creates barriers to achieving sustainability and operational efficiency. For this purpose, the study take DfD strategies into account; the use of disassembly indices such as the complexity index (Icom) and U-effort can deal with these difficulties. These methods give valuable insights that can support maintenance optimization, lifecycle cost reduction and, thus, sustainability through optimized resource recovery. The DfD principles are applied to redesign the gas knob and redesign of the speed reducer gearbox, as a case study through which it is demonstrated that how DfD can revolutionize practices in Mechanical engineering for a better tomorrow.

1.3 Objective of the study

This study aims to investigate the impact of design modifications on the disassembly performance of a gas knob and a speed reducer gearbox with the goal of improving their maintainability, recyclability, and overall sustainability. The primary objective is to reduce disassembly effort and improve material recovery through the systematic application of DfD principles and the utilization of disassembly indices. By addressing the challenges associated with current disassembly practices, this research aims to contribute to the development of more sustainable and environmentally friendly product designs. To achieve this, the study will employ a combination of CAD modeling and the analysis of disassembly on DeSE Software.

The study will:

- Identify and quantify the current disassembly challenges associated with the existing designs.
- Develop and evaluate design modifications that improve the easiness of disassembly and reduce disassembly effort.
- Demonstrate the potential for improved disassembly performance through the application of DfD principles.
- Contribute to a better understanding of the relationship between design decisions and disassembly performance in mechanical components.

1.4 The scope of the study

The study discusses the potential improvement in the disassembly performance of a gas knob and a speed reducer gearbox through design improvement. With a focus on the principles of DfD, the research accentuates practical approaches to facilitate and improve the disassembly of the parts. Instead of putting emphasis on the reduction of disassembly time alone, the study places greater emphasis on investigating the complexity and effort required in the disassembly process. The system also integrates basic mechanical engineering principles involving interaction and integration of components like shafts, gears, oil seals, retaining rings, and flanges to deliver functionality as well as compatibility in the re-designed components.

The redesigning process is primarily based on three major strategies:

- Reducing the number of fasteners to allow easier disassembly.
- Reducing the incidence of strong interference fit connections to make separation of the components easier.
- Utilizing snap-fit mechanisms where applicable, which allows quicker and tool-free disassembly.

These techniques are intended to ease assembly and disassembly, improve accessibility, and minimize specialized tool needs. Concurrently, the research preserves the mechanical fit, alignment, and general functionality of the redesigned parts. Yet, it does not address in-depth analyses like stress analysis, load-carrying capacity, or force simulations for the redesigned parts. Rather, emphasis is placed on pragmatic implementation of DfD concepts for improved disassembly performance.

Fundamental DfD principles such as modularity, standardization, and reversible joints are the bases of this study. These principles allow the gas knob and speed reducer gearbox to be easily maintained, recycled, and reused without compromising functional performance. For example, modularity gives easier access to key components, standardization minimizes tooling, and snap-fit interfaces dispense with conventional fasteners, which make part removal easier.

To achieve these goals, the research utilizes modern tools and computer software. The CAD design software Solid Edge facilitates virtual prototyping, which in turn facilitates evaluation of design changes in depth. Additionally, there is application of disassembly analysis software such as DeSE to calculate different metrics such as *Icom*. These metrics provide quantitative information regarding the success of the design changes, which provides overall evaluation of disassembly effort and complexity instead of focusing on disassembly time only.

With this specific focus, the research makes it possible to design mechanical products that are maintainable and sustainable. The research does ensure that reengineered components attain an optimal rate of balance between performance and ease of disassemble while, at the same time, reducing unnecessary complexity and redundancy. This research aims at simplifying designs to meet functional needs as well as sustainability needs.

1.5 Significance of the study

The importance of this study is that it clearly deals with the problems of reducing the effort involved in the disassembly of mechanical components, a gas knob and a speed reducer gearbox, using the concepts of DfD. The research is interested in the evaluation and improvement of factors like tool complexity, accessibility, and assembly configurations rather than focusing on the disassembly time. In this manner, it attempts to provide practical information to engineers and manufacturers so that they can design products that are easier to maintain, repair, and recycle with minimal disassembly effort.

Minimization of effort in disassembly is a central problem that impacts maintenance as well as recyclability. Designs involving high numbers of fasteners, interference fits, or inaccessible components entail high physical and technical effort in disassembly. The above problems can lead to delays, damage to components, and higher labor costs. The redesigned components presented here by minimizing the number of fasteners, minimizing the extent of strong interference fit connections, and adding snap-fit mechanisms will be simpler to disassemble. This modification directly benefits maintenance personnel by making it simpler and reducing the extent of skill or tools required while lowering the likelihood of component damage during repair or recycling operations.

From a sustainability viewpoint, reducing disassembly effort makes products more recyclable. Systems with less disassembly effort make material separation easier, hence more efficient recycling. This is most applicable to promoting a circular economy where materials are cycled back and recycled continually to minimize waste to the environment. Through the application of DfD principles such as standardization, modularity, and joint reversibility, this study guarantees that disassembly is readily available and takes minimal or no effort, thus increasing the prospects for valuable material recovery and minimization of landfill waste.

The research also demonstrates the potential of sophisticated modeling and analysis tools to support the design process so that these objectives are achieved. Software such as CAD software (more specifically Solid Edge) and disassembly analysis software (specifically DeSE-Design for Sustainability and Environment) enable quantification of disassembly operations by measures such as the Complexity Index (Icom). This empirical method detects effort minimization by identifying bottlenecks and inefficiencies in existing designs, thereby providing a systematic way of performing focused design improvement.

By focusing on the disassembly effort, this study provides practical value to various stakeholders. To maintenance staff, it reduces physical and technical challenges in accessing and servicing different components. To manufacturers, it reduces maintenance cost while making their products more appealing to customers who value serviceability. To environmentalists, it achieves sustainability goals by enabling disassembly and recycling of components and thus reducing their environmental footprint.

Finally, this study adds to the expanding literature on sustainable mechanical design by illustrating the way in which the minimization of effort required for disassembly can play an important role in efficient, maintainable, and environmentally responsible products. It distinctly shows that there is a clear link between design choices and its effect on effort minimization and so it calls for the application of DfD principles by engineers to develop functional, cost-effective, and environmentally friendly products.

PART TWO- LITERATURE REVIEW

The increased emphasis on sustainability has driven DfD into a necessary consideration for product design, particularly for mechanical systems. DfD enables product design to prioritize maintenance, repair, and recycling at the end of life, thereby realizing resource efficiency and minimizing the environmental impact. This chapter discusses existing research on disassembly principles, complexity measures, and their incorporation in redesigning the speed reducer gearbox and the gas knob (gate valve).

2.1 Design for disassembly (DfD) and life cycle assessment (LCA)

DfD and LCA provides a promising approach towards sustainable product development, allowing for the management of resource efficiency and environmental performance trade-offs. Analyzing the intersection of theory and practice for environmental impact mitigation is the bridge that is filled with abstract design principles.

LCA is a holistic analysis framework for assessing the environmental impacts over the entire life of a product. The combination of DfD and LCA represents a robust approach to addressing environmental impacts from product development to end-of-life decisions. According to their research, this method allows designers and engineers to make more holistic decisions that go beyond traditional performance metrics [14].

The material selection plays a significant role in this combined approach. Researchers such as Graedel and Allenby have stressed that material choices are one of the most important factors to influence the environmental footprint of a product. Through the DfD-LCA framework, such material properties can be refined for this analysis with factors like recyclability, embodied energy, reuse potential, and end-of-life impact all contributing to the end value of a given structural material. This strategy goes beyond conventional material selection criteria and enables integrated environmental assessment over the lifecycle of the product [3].

Connection design is one other critical feature in the DfD-LCA methodology. According to Wimmer and Züst, The complexity and nature of the connections directly impact disassembly efficacy and materials recovery potential. Their research shows how through the strategic design of connections and fastenings used in disassembly, energy consumption can be minimized by up to 30%, hence boosting both environmental performance and economic viability [20].

Disassembly energy usage is a key research topic in this integrated DfD-LCA methodology. For example, Sundin modeled methodological contributions that quantify the energy required for alternative disassembly strategies, giving designers tools to maximize the environmental benefits. Considering the energy consumption for tools, humans, and the mechanical separation process, these models provide a comprehensive understanding of energy utilization in EOL product management [17].

When considering product lifecycles, separation becomes an important design parameter. Researcher such as Ijomah created an advanced system for measuring the complexity of separation with respect to geometric restrictions, material interphases and connecting techniques. Their work shows that better designed separation process could potentially enhance the recovery rate of materials by 40-50% [8], which could help reduce the overall waste and environmental impact.

Technological evolution is also broadening the scope of the existing DfD-LCA methodologies. Our data-driven digital simulation tools and advanced computational models provide accurate predictions of environmental impact in the early design phase. These technologies allow for the simulation of many scenarios, the optimization of material choices, and lifecycle environmental performance predictions with a hitherto unimaginable level of realism.

As the DfD-LCA paradigm cuts across several domains like materials science, environmental engineering, design engineering, economic analysis, etc., multi-disciplinary collaboration for DfD-LCA is a necessity. It understands that sustainable design is not available as one-size-fits-all interventions, but must instead be approached with a systemic, integrated mindset.

Although tremendous progress has been made toward implementing DfD-LCA methodologies, it has not yet been fully deployed. Inconsistencies in industry practices, economic pressures and technological challenges remain hurdles. In addition, future research must also be directed towards the establishment of standardized frameworks for assessment, the development of computational tools (e.g. software for design modelling), the creation of economic incentives in favor of sustainable design processes.

The integrated DfD-LCA approach has significant practical implications. In doing so, this methodology contributes a holistic framework for understanding environmental impacts, ultimately enabling designers and manufacturers to design and manufacture more sustainable products. This approach goes beyond the traditional design drivers; it's an entire framework to reduce environmental footprints, and to do so economically.

2.2 Design for Disassembly Principles

DfD principles provide the basis for realizing circular economy objectives in terms of simplified recovery, reuse, or recycling of parts. Modularity, material compatibility, and reversible joints are the key principles, each intended to minimize disassembly effort.

2.2.1 Design Modularity

Modular designs divide a product into distinct subassemblies or modules for facilitating easier replacement, maintenance, and recycling. Rose and Stevels showed that modularity can cut disassembly effort and material waste by up to 30% [15]. For the speed reducer gearbox, modularity in gears, shafts, and bearings allows components to be easily separated during disassembly, making material recovery faster. In addition, the redesign of the gas knob can capitalize on modularity, with plastic and metal parts being separated for ease of recycling.

2.2.2 Material Compatibility

Material choice is very important in DfD. Mono-material parts and avoidance of mixed material to make recycling easier. For instance, the use of a single recyclable material (e.g., steel or aluminum) in gearbox housing parts obviates subsequent separation processes. In gas knobs, substituting snap-fits or press-fits with adhesive-bonded mixed materials will significantly increase recyclability [9].

2.2.3 Reversible Joints

The application of reversible joints, including screws, bolts, and snap-fits, is a fundamental principle of DfD. Reversible joints enable disassembly without causing damage to components, which makes recycling or reuse of components possible [5]. The gearbox and gas knob are parts connected by interference fits or permanent fasteners. Their substitution with reversible joints would minimize disassembly effort and costs.

2.3 Design for Disassembly (DfD)

DfD is a paradigm shift of large magnitude in the field of sustainable product design, aimed at addressing fundamental end-of-life problems in mechanical systems. Theoretical underpinnings are drawn from the urgent need to re-engineer traditional linear manufacturing approaches into circular economy models. Pioneering research by Sundin and Björkman (places DfD as a core methodology for designing products that can be readily disassembled, recycled, and returned to production systems [18].

The complexity of connections is a central theme in DfD research. Scholars like Kiritsis have created hierarchical models to comprehend the complexity of connections, categorizing them as primary structural connections, secondary auxiliary attachments, and tertiary supplementary interfaces [12]. Such in-depth knowledge enables designers to effectively reduce connection complexity by standardizing connection types, employing reversible joining techniques, and favoring modular design approaches like snap-fit or clip-based connections.

Component reuse is the ultimate of DfD's eco-design practice. There is ample evidence, as presented by Ijomah that good DfD practice can achieve product life extension by 40-60% and material waste reduction by as much as 35%. The study highlights material homogeneity, minimum material contamination, and material property retention [8]. New practices involve the design of modular design structures, choosing materials of high recyclability, and creating standardized component interfaces.

The theoretical framework applies traditional engineering methods to include environmental science information, materials engineering, and economic analysis. More sophisticated reusability strategies are proposed by researchers that consider material quality factors, connectivity complexity, and component integrity. The multi-disciplinary approach recognizes that the realization of sustainable design relies on an integrated product lifecycle understanding.

Contemporary DfD research is increasingly utilizing cutting-edge technologies such as digital disassembly simulation, artificial intelligence-driven design, and predictive modeling. These technologies overcome past limitations in comprehending intricate product designs and overcoming performance and economic limitations.

Despite significant advancements, challenges persist. Researchers are currently working to resolve methods for harmonizing design complexity, performance requirements, and sustainability goals. The evolving framework shows that DfD is not an immutable rule but an adaptable method that requires constant innovation and collaboration between diverse disciplines.

The real-world applications of DfD are significant. By remapping product design with disassembly and reuse as goals, scientists and engineers can significantly minimize environmental effects, decrease lifecycle costs, and develop more sustainable manufacturing systems. The theoretical model offers an overarching guide to transforming product design from a linear, wasteful system to a circular, resource-efficient system.

With increasing worldwide sustainability challenges, the DfD strategy provides a promising route to more sustainable and innovative product design practices. Future research will probably concentrate on future simulation technology, machine learning in disassembly prediction, and the creation of standardized assessment frameworks that can be used in various manufacturing industries.

Disassembly complexity is a critical issue in ease analysis with regard to disassembly ease of a product for processing at EoL such as remanufacturing and recycling. Individual part and subassembly shape and physical characteristics, according to Soh form disassembly complexity and can render disassembly a challenge with regard to ease in handling and disassembly. In a bid to tackle such a challenge, the study proposed a disassembly complexity index for assigning a numerical value for ease with a disassembly of a product can be performed with regard to two key factors, including handing complexity and disassembly complexity [16].

The **complexity index (*I_{com}*)** is calculated as the average of the handling complexity (C_h) and removal complexity (C_r) indices, as shown in Eq. 1:

$$I'com = \frac{C'_h + C'_r}{2} \qquad \textit{Eq. 1}$$

Where:

- C'_h – Indicates **average handling complexity factor**, and
- C'_r– Indicates the **average removal complexity factor**.

This balanced approach ensures that both handling and removal complexities are given equal weight in the overall evaluation of disassembly difficulty.

2.3.1 Handling Complexity (C_h)

Handling complexity refers to the challenges associated with manipulating individual parts during disassembly. It is influenced by three key attributes: **size**, **thickness**, and **mass**. The handling complexity index (C_h) is calculated using Eq. 2 and Eq. 3:

$$C'_h = \frac{C_{h,f}}{3} \qquad \textit{Eq. 2}$$

$$C_{h,f} = Rating_{Size} + Rating_{Thickness} + Rating_{Mass} \quad \text{Eq. 3}$$

Here, $C_{h,f}$ represents the sum of the ratings for size, thickness, and mass. These ratings are derived from the physical dimensions and weight of the part, as described below.

I. Size and Thickness Calculations

The **size** and **thickness** of a part are calculated based on its dimensions. Thickness is defined as the smallest dimension of the bounding box (Eq. 4), while size is calculated as the diagonal of the bounding box surface (Eq. 5):

$$Thickness' = \min(x, y, z) \quad \text{Eq. 4}$$

$$Size' = \sqrt{(\max(x, y, z))^2 + (sum\ (x, y, z) - \max(x, y, z) - \min(x, y, z))^2} \quad \text{Eq. 5}$$

These calculations ensure that the size and thickness are determined objectively, independent of the coordinate system. Figure 2 illustrates how size and thickness are identified geometrically [21].

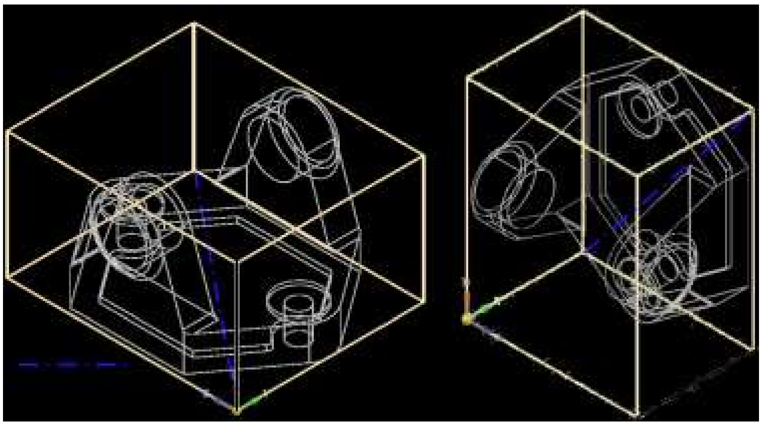


Figure 1 Example of Size and Thickness identification

II. Operation Type (OT)

The **operation type (OT)** is determined based on the mass and size of the object, as outlined in Table 1. The operation type can be classified as **one-hand (OH)**, **two-hand (TH)**, or **automated (A)**, depending on the mass and size thresholds.

Table 1 Definition of Operation Type (OT). OH = one hand, TH = two hands, A = Automation

	Mass [kg]					
Size [mm]	**<1.125**	**<2.25**	**<3.375**	**<4.5**	**<20**	**>20**
<38	OH	OH	OH	OH	TH	A
<70	OH	OH	TH	TH	TH	A
>70	TH	TH	TH	TH	TH	A

III. Ratings for Size, Thickness, and Mass

The ratings for size, thickness, and mass are calculated using continuous functions. For example, the rating for size ($Rating_{Size}$) is calculated differently for one-hand and two-hand operations, as shown in Eq. 6 and Eq. 7:

$$R'_{Size}\begin{cases} OH = \ 0.0003 * Size^2 - 0.0239 * Size + \ 0{,}9887 & \text{Eq. 6} \\ TH = \ 10^{-6} * Size^2 - 0.0013 * Size + 0.8983 & \text{Eq. 7} \end{cases}$$

Similarly, the rating for thickness ($Rating_{Thickness}$) is calculated using continuous functions for one-hand and two-hand operations, as shown in Eq. 8 and Eq. 9:

$$Rating'_{Thicness}\begin{cases} OH \ = 0.0003 * Thickness^2 - 0.0199 * Thicness + 0.8703 & \text{Eq. 8} \\ TH = 10^{-6} * Thickness^2 - 0.0013 * Thicness + 0.898 & \text{Eq. 9} \end{cases}$$

The rating for mass ($Rating_{Mass}$) is determined based on predefined ranges, as shown in Table 2.

Table 2 Definition of Rating Mass

Mass [kg]	Rating
0	0
(0 , 1.125]	0
(1.125, 2.25]	1.125
(2.25, 3.375]	2.25
(3.375, 4.5]	3.375

2.3.2 Removal Complexity (Cr)

Removal complexity refers to the challenges associated with unfastening or separating parts during disassembly. It is influenced by factors such as the **number of tools required**, the **type**

of operation, and the **effort needed to unfasten components**. The removal complexity index (C_r) is calculated as shown in Eq. 10 and Eq. 11 :

$$C'_r = \sum_{1}^{K} C'_{r,i} \qquad \text{Eq. 10}$$

$$C'_{r,i} = \frac{U'_{effort} + \frac{R'_{NumT} + R'_{TR} + R'_{OT}}{3}}{2 * N_{pl}} \qquad \text{Eq. 11}$$

Where:

- U'_{effort} represents the **mechanical unfastening effort**,
- R'_{NumT} represents the **rating for the number of tools required**,
- R'_{TR} represents the **rating for the type of tools required**, and
- R'_{OT} represents the **rating for the operation type**.

Tables 3, 4, and 5 define the ratings for the number of tools required (RatingNumber of Tools Required), tools required (Rating Tools Required), and operation type (Rating Operation Type), respectively.

Table 3 Definition of Rating Tools Required

Number of Tools	Rating
0 tools	0
1 tool	0.3
2-3 tools	0.6
>4 tools	1

Table 4 Definition of Rating Number of Tools Required

Tools Required	Rating
None	0
Air gun	0.3
Mechanic	0.6
Special	1

Table 5 Definition of Rating Operation Type

Operation Type	Rating
None	0
One-hand	0.3
Two-hand	0.6

Automation	1

IV. Fastener and Non-Fastener Ratings

The type of connection is classified as either **fastener** or **non-fastener**, with the unfastening effort (U_{effort} calculated based on the type of fastener used, as shown in Eq. 12:

$$U'_{effort} = Rating'_{Fastener} * Number\ of\ fastener \qquad Eq.\ 12$$

The ratings for fasteners and non-fasteners are defined in Tables 6 and 7, respectively.

Table 6 Definition of Rating Fastener

Fastener	Rating	Number of Tools	Tools Required
Retaining Rings/Circlips	0.83	1 tool	Mechanic
Screw specialty head	0.73	1 tool	Special
Nut	0.13	1 tool	Mechanic
Adhesive	0.70	0 tools	None
Rivets/Staples	0.67	1 tool	Mechanic
Nail w/o head or Pin	0.60	1 tool	Mechanic
Releasable Clips	0.60	0 tools	None
Tape	0.57	0 tools	None
Nail with Head	0.50	1 tool	Mechanic
Screw standard head	0.47	1 tool	Mechanic
Glued screw standard head	0.83	2 tools	Mechanic
Velcro/Zipper	0.33	0 tools	None
Free Part	0	0 tools	None

Table 7 Definition of Rating No Fastener

No Fastener	Rating	Number of Tools	Tools Required
Interference Fit_weak	0.63	1 tool	Air gun
Interference Fit_strong	1.00	2-3 tools	Mechanic
Integrally Threaded Part	0.73	1 tool	Mechanic
Cylindrical Snapfit	0.53	0 tools	None
Seam/Crimp Joint	0.53	0 tools	None
Cantilever Snapfit	0.43	0 tools	None
Socket and Plug	0.40	0 tools	None
Free Part	0	0 tools	None

2.4 Disassembly Complexity Indices

Quantification of disassembly operations is necessary to implement DfD effectively. Disassembly complexity indices assist in formulating a framework for evaluating and enhancing design from the perspective of disassembly ease.

2.4.1 Past Development of Disassembly Indices

One of the earliest indices was suggested by Boothroyd and Alting focusing on reducing time taken in disassembly operations [1]. While time is crucial, current work focuses on effort-based indices to represent the mechanical complexity of the operation.

Soh expanded these indices to include features such as geometric constraints, tool accessibility, and material interaction. These expansions are in line with the difficulties posed by the speed reducer gearbox and gas knob, whose miniaturization and composite materials make disassembly difficult [16].

2.4.2 Software Tools for Disassembly Index Evaluation

DeSE software is a part of this research that enables researchers to compute disassembly indices through automated calculations. Once 3D modeling is done in Solid Edge, analysis using DeSE is employed to measure disassembly effort while keeping in mind material compatibility, types of fasteners, and joint types. This interplay enables effective assessment and redesigns based on data, particularly for complex assemblies like the gearbox and gas knob.

2.4.3 Complexity Index (*Icom*)

The Complexity Index (*Icom*) was initially conceived as a tool to assess the intricacy of designs, considering factors like the number of parts, their interactions, and the complexity of manufacturing processes (Pahl & Beitz, 2007). Imagine it as a way to quantify how "messy" a design is from an engineering standpoint. This early framework laid the groundwork for understanding how design decisions impact various aspects of product development, particularly manufacturability.

Building upon this foundation, researchers began to explore the broader implications of *Icom*. Ulrich and Eppinger (2016) expanded its scope to include design for assembly, emphasizing how *Icom* can help predict and mitigate potential bottlenecks in the production process. Essentially, *Icom* started to reveal how the complexity of a design can translate into real-world challenges on the factory floor.

However, the focus soon shifted towards a more pressing concern: the environmental impact of products at their end-of-life. As the need for sustainable practices grew, researchers began to adapt *Icom* to assess disassembly complexity. This shift in perspective recognized that a truly "good" design not only considers how easily it can be made but also how easily it can be taken apart for recycling or reuse.

To make *Icom* more relevant to the disassembly challenge, researchers simplified the calculation. Instead of considering a broad range of factors, they focused on two key aspects:

- **Handling Complexity (C'_h):** This captures the difficulty of physically interacting with the product during disassembly. Imagine trying to maneuver a large, heavy component with awkward shapes or sharp edges – that's where high handling complexity comes into play.
- **Removal Complexity (C'_r):** This focuses on the challenge of separating individual components from the assembly. Factors like the type of joints used (screws, welds, adhesives), the presence of tight fits, and the need for specialized tools all contribute to removal complexity.

Jones and Thorn (2003) formalized this simplified *Icom* approach, expressing it as the average of Handling and Removal Complexity. This concise formula provides a practical tool for designers to quickly assess the disassembly implications of their choices.

The beauty of this simplified *Icom* lies in its direct connection to DfD principles. By focusing on reducing both Handling and Removal Complexity, designers can actively incorporate strategies like:

- **Modularity:** Breaking down the product into smaller, easily separable subassemblies, much like a Lego set.
- **Standardization:** Using common, easily accessible fasteners and joining techniques, minimizing the need for specialized tools.
- **Reversible Joints:** Employing connections that can be easily undone without damaging the components, such as snap-fits or certain types of screws.

These DfD principles, championed by experts like Gray (2006) and McDonough & Braungart (2002), aim to create products that not only function well but also gracefully transition from use to their end-of-life, minimizing waste and maximizing the potential for material recovery.

In essence, the simplified *Icom* has become a powerful tool for guiding design decisions towards a more sustainable future. By quantifying the disassembly challenge and providing a clear target for improvement, it empowers designers to create products that are not only functional and aesthetically pleasing but also environmentally responsible throughout their entire lifecycle.

2.5 Disassembly Effort

Soh also developed the disassembly effort by adding manipulation complexities to the evaluation model. The new disassembly indices quantified the physical effort, tool availability, and technical challenges in the component separation. This systematic process provided a platform for disassembling and optimizing disassembly designs to minimize effort without affecting product function [16].

Mechanical components like the speed reducer gearbox and gas knob present high disassembly effort because of highly integrated neighboring parts, many fasteners, and material mixture. High U-effort ratings mean that some parts take too much physical effort or need special tools to detach and are hindrances to maintenance and recycling. To enhance this, fastener location should be optimized, interference fits minimized, and permanent joining methods like adhesives or welds avoided (Gupta & Lambert, 2006).

Veerakamolmal and Gupta (1999) also pointed out the importance of material compatibility in reducing the effort involved in disassembly. The use of mono-material designs and the elimination of incompatible materials (such as bonding plastic and metal) lead to easier disassembly and environmental friendliness. For example, in the gas knob, disassembly of plastic and metal components can aid recycling activities, while in the gearbox, modular configurations that subdivide gears, bearings, and housings reduce the extent of manual work needed for dismantling.

The economic implication of disassembly effort is significant. Chiodo and McDonough (1998) noted that manual disassembly not only increases recycling expense but also lowers the economic viability of product recovery. The presence of reversible joints, such as snap-fits or standard screws, can notably minimize disassembly effort and improve end-of-life processing overall cost-effectiveness.

2.6 Applications in Mechanical Systems

Gas knob and speed reducer gearbox are examples of the issues in implementing DfD principles.

2.6.1 Speed Reducer Gearbox

A speed reducer gearbox is characterized by a robust and tightly packaged structure with a large amount of fasteners, interference fit, and elastic material joints. Although such features are required to provide performance, they also pose disassembly challenges. The integration of modularity and reversible joints in the gearbox design can allow for easy removal of gears, shafts, and bearings for recycling and maintenance purposes. A case study by Gupta and Lambert (2006) highlights the importance of such strategies in reducing overall disassembly cost.

2.6.2 Gas Knob (Gate Valve)

The complex structure of the metal-plastic composite in the form of a mixture of metal and plastics creates a big challenge in disassembly during the recycling stage. Despite using snap-fit and week-fit joints in assembly, and therefore not having adhesive bonding, disassembly with a variety of materials necessitates careful disassembly for effective material retrieval. Enhancement of such connecting techniques for ease in disassembly will not only save cost but will promote effective material retrieval and reiterate the findings of Kahmeyer and Warneke (1993) regarding disassembly connecting techniques' critical role in disassembly design.

2.7 Disassembly Challenges in Mechanical components

Gearboxes are critical components in industrial and automotive applications and are notoriously difficult to tear apart. Their structural complexity with precisely aligned shafts, gears, bearings, and seals, requires specialized tooling and technique [6].

The use of interference fits is one of the primary reasons for not being able to separate several components of a gearbox [10]. The joining with small dimensional interferences leads to and ensures correct functionality and load-carrying capacity, the obtaining of such fits is an achievement. This joining process creates tight mechanical joints that are not prone to loosening or separation of parts during regular operating conditions. But the need for significant applied force to unsecure these tightly fitting interfaces on disassembly can cause permanent and irreversible damage to the interfaces, in the form of bending, cracking, or even breaking. Hardened steel parts are then particularly unyielding, typical of applications found in high-performance gearboxes, and more sensitive to any forms of misalignment [10].

There are adhesives and sealants which make disassembly harder. While key for providing good sealing, lubrication, and leak resistance, these materials form strong bonds that are very difficult to destroy without damaging the components [10]. To remove the seals without damaging the seals themselves or the adjacent surfaces, it usually entails the application of gentle heat, application of appropriate solvents, or use of the designed removal tools for that purpose. One potential positive strategy could be the use of the appropriate adhesives during the design process with controlled bond strengths that enabled disassembly.

Corrosion can make things even more complex for disassembly. Corrosion may develop in the gaps between components over time, particularly in humid, chemical, or high- or low-temperature environments [4]. This corrosion can lead to parts welding together, rendering disassembly extremely difficult and sometimes destructive. Rust or other corrosive products, bind parts together, requiring tremendous force and the potential for destroying surfaces when disassembled. Using corroding protection that is applied at the houses of the factories during manufacturing, and using some corrosion-resistant materials also reduce this problem.

Non-Standard Geometries particularly the case for gearbox parts, which have complex geometries. The complexity of internal shapes of gears, bearings, and housings as well as the small clearances between their parts may restrict access [1] under these conditions, using force or special tools when a disassembly in progress makes such operations more complex and significantly increases the risk of destruction.

To resolve the challenges of dismemberment of gearing there are many solutions that can be recommended. Specific concern is related to the DfD [13]. By introducing DfD concepts during the early stages of design, engineers can choose joining methods; e.g., fasteners or adhesives with limited bond strengths that enable disassembly. Using standardized parts and modular construction, these two methods can facilitate disassembly and reduce the need for specialized equipment. Including disassembly features in the design, like access holes, alignment pins, and quick-release fasteners, can really make a difference when disassembling.

Typically, some level of equipment and tools are required to safely and successfully extract components. Removing a press-fitted part or breaking a tight fit, which can be difficult, can be solved with Hydraulic presses. Tools such as heating devices can sometimes help loosen adhesives for removal. Using extractor tools (such as bearing pullers or gear pullers) can also reduce the odds of damaging the surrounding components during removal.

In the disassembly process, guides to ensure proper disassembly techniques to guide technicians down the correct process of disassembly play a large part in the operation. The guides should include graduated procedures, safety protocols, and special tool usage advice.

PART THREE- METHODOLOGY

3.1 Methodological Framework of the Study

The study adopts a scientific and organized methodology for the application of DfD principles. The main objective is to enhance the disassembly process and environmental performance of a speed reducer gearbox and a gas knob. With a research-oriented methodology, the study focuses on evaluating the current design of the assembly and identifying enhancements that enable disassemble, increase recyclability, and reduce environmental impact. The methodology is initiated with the study of the physical parts of the original products and the subsequent generation of virtual 3D models that are replicating these parts with accuracy. The models are then studied using DeSE software to consider the important factors like disassembly complexity and scope for recyclability. This is done iteratively in a way that DfD principles are applied while quantitatively and qualitatively enhancing the design with improved environmental performance.

This framework shown in Figure 1 presents a detailed and sequential method for applying DfD ideas to enhance the disassembly performance and ecological fitness of mechanical assemblies, through product examples such as a speed reducer gearbox and a gas knob. This consists of reverse engineering, computer simulation, analysis of disassembly difficulty, and design iterations facilitated with sophisticated software tools such as Solid Edge and DeSE. With the focus on recyclability, environmental impact, and ease of disassembly, this model will create products that are sustainable and efficient.

3.2 Methodology Phases

Research methodology is segmented into a number of interdependent steps, whose steps are designed to play crucial roles in helping in ensuring the set goals are achieved:

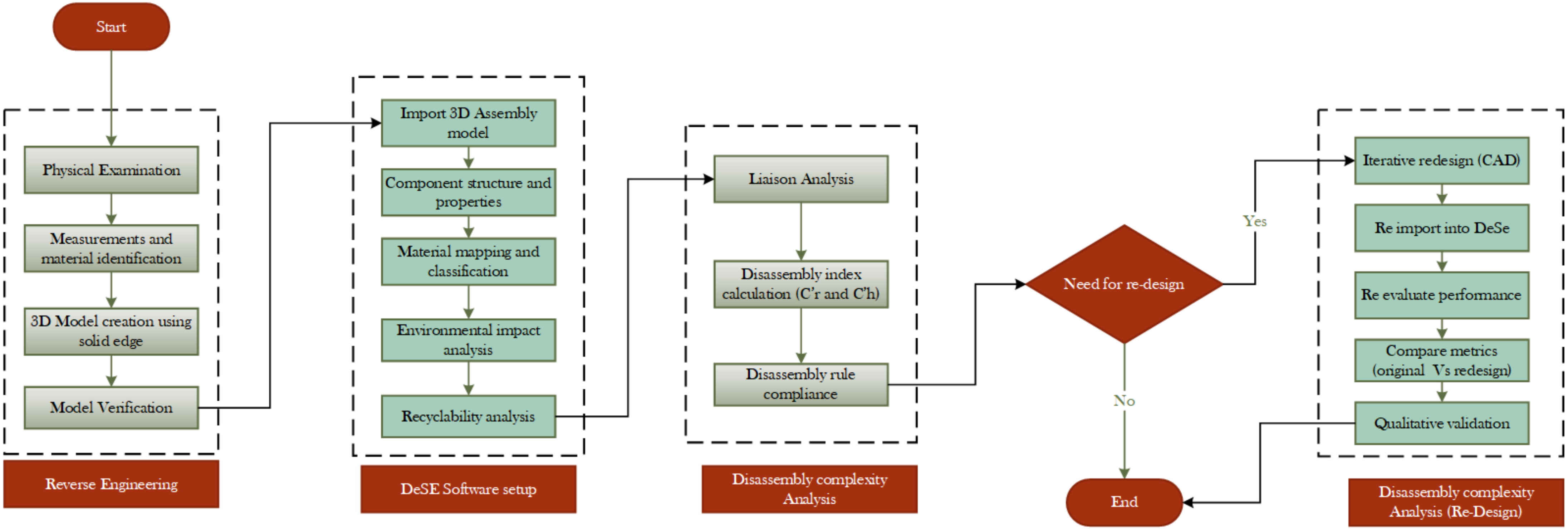


Figure 2 Methodology Framework for DfD

3.2.1 Reverse Engineering of Existing Designs

The first step involves the reverse engineering of existing designs of the speed reducer gearbox and gas knob. This process starts with carrying out a detailed physical inspection of the original components, then proceeding to develop accurate digital models in CAD environment. Physical characteristics are measured through measurements that is, their dimensions-length, width, and height with Vernier caliper. Types of materials are identified visually or from the manufacturer's catalogue. Physical characteristics are also carefully documented by research in the studies, for instance, fasteners, interference fits, and a range of joining techniques, to enable a holistic study of the existing design.

After the data is gathered, 3D models of all the parts are developed through Solid Edge software. The models mirror the size and physical characteristics of the original parts, such as the materials and the joining techniques used in the assembly. To confirm that the digital models truly reflect the physical parts, they are rigorously checked by comparing them to the original parts. Any inconsistency is detected and rectified prior to utilizing the models in subsequent analysis. The process forms the foundation of the whole study by creating a consistent digital model of the assembly for thorough assessment.

3.2.2 Import and Setup in DeSE Software

Following the development of precise 3D models, the second process is their importation into DeSE software for analysis of the disassembly complexity, recyclability, and environmental performance of the assembly. DeSE software is utilized to analyze the disassembly complexity of the assembly, calculate disassembly indices such as the *Icom*, and assess the environmental impact of different end-of-life scenarios. In the Component Structure Tab of the software, virtual assembly generated by Solid Edge is imported, and attributes of every component such as the name of the component, material, weight, and dimensions are inspected and documented. Atomic components, i.e., those objects which is not expected to be broken down, are identified, and all the pieces are classified based on their respective functions (e.g., fasteners, functional parts, etc.).

Manual mapping is performed for any of the parts not identified by the software itself. These involve the identification of material properties, grouping of parts, and establishing naming conventions under the requirements of the specific project. Environmental impacts are also assessed based on default environmental indicators such as climate change (Kg CO_2 eq), ozone layer depletion (Kg CFC11 eq), natural resource depletion (Kg Sb eq), land use (m^2a), and eutrophication (Kg PO_4 eq), etc. All these analyses decide how the overall environmental performance of the assembly is affected when using various End-of-Life (EOL) management strategies like landfilling or incineration.

The potential for recyclability of the assembly is also being tested. To determine this, the weight of each component, the types of materials used, and their associated environmental effects are included in the calculation of the recyclability indices. The raw material content in each part is also analyzed to ascertain its contribution to the total weight and material content of the assembly. The results of these analyses are shown in pie charts, graphs, and tabular reports that provide keen information about the environmental performance and recyclability of the original design.

3.2.3 Disassembly Complexity Analysis

Phase three involves evaluating the disassembly complexity of the original and redesigned components using the liaison and disassembly analysis tools in DeSE software. In the Liaison View Tab, the relationships or connections between the subassemblies and the parts are identified and evaluated. These relationships, such as the fasteners, interference fits, and other joining technologies, are identified automatically by the software. Discrepancies in the detection process are manually corrected to ensure the accuracy of the analysis.

The Disassembly Index Tab is then used to calculate important disassembly indices such as the *C'h* and the *C'r*. These are the measures of removal effort and handling effort of the components involved in the disassembly process. The results are demonstrated in bar charts that detail the complexity of each of the components, thereby rendering it less difficult to identify parts that are hard to disassemble. The disassembly regulations compliance is also examined in an attempt to identify critical components that could be problematic in the disassembly procedure. Warning symbols (yellow and red color applied) are used to represent components requiring improvement, while green symbols denote components that comply with the established disassembly criteria.

3.2.4 Redesign Assessment

The redesign process is iterative in nature and aimed at improving the disassembly and sustainability performance of the assembly. This iterative process involves continuous refinement of the design based on the results of the disassembly rules and the analysis of disassembly indices. Outcomes of the analyses performed by DeSE software on the initial design guide the first stage of redesign. Specific problems, such as high disassembly complexity and low recyclability, are addressed through changes developed in the CAD environment. The redesigned parts are virtually reassembled to check their compatibility and functionality.

These redesigned models are then re-inputted into the DeSE software for re-evaluation. The same procedure of analysis is duplicated, e.g., moving from the Component Structure Tab to the Disassembly Index Tab, to measure the improvement gained through redesign. The process is repetitive and goes on until the desired levels of disassembly complexity, recyclability, and environmental performance are reached. Quantitative indices, such as disassembly indices and recyclability indices, are compared for the original and altered components in a bid to describe the success of the alterations. Additionally, qualitative verification ensures that the altered components are more convenient, require fewer tools to disassemble, and minimize the risk of damage in the process.

3.2.5 Exclusions

In order to keep in mind a focused scope, the study excludes some things from its procedure. These are mechanical stress analysis by load-bearing capacity and stress forces, and time-based disassembly testing since the study focuses more on effort and complexity rather than time. Physical prototyping is not performed; rather, the study uses virtual simulations achieved by means of CAD and DeSE software.

3.2.6 Tools and Software Used

The process uses a variety of sophisticated tools to ensure scientific precision and accuracy. Solid Edge software is utilized in the designing and simulation of 3D models of the components and assembly, while DeSE software determines disassembly complexity, recyclability, and environmental footprint. Several measures and indices, including complexity indices (*C'h and C'r*), recyclability indices, and environmental footprint indicators, are used in determining the performance of both the original and redesigned assemblies.

The methodological framework outlined in this study provides a systematic approach to applying DfD principles to the speed reducer gearbox and gas knob. Through reverse engineering, virtual modeling, and iterative redesign, the study successfully identifies opportunities to enhance disassembly performance, recyclability, and environmental sustainability.

PART FOUR- FINDINGS AND RESULTS

This chapter introduces disassembly complexity analysis for two case studies: a gearbox for a speed reducer and a gas knob. For both cases, analysis utilizes DeSE software to assess disassembly factors such as key ones, namely, the *C'h* and the *C'r*, and disassembly compliance with predefined disassembly rules in DeSE. The output of such analysis identifies disassembly difficulty for both products and guides improvement in DfD.

4.1 Speed Reducer Gearbox

A speed reducer gearbox is a mechanical gearbox that takes an engine's or a motor's input speed and, in a similar proportion, raises its output torque. In automotive and industrial use, a gearbox is one of the most significant aspects that ensure proper force transmission and maximize performance in machines. With gears, shafts, and bearings in combination, a gearbox realizes a high level of accuracy in its speed and load management, and therefore, it constitutes a critical part in motion control in a system. An illustration of the project work’s gearbox for a speed reducer is presented in figure 3:

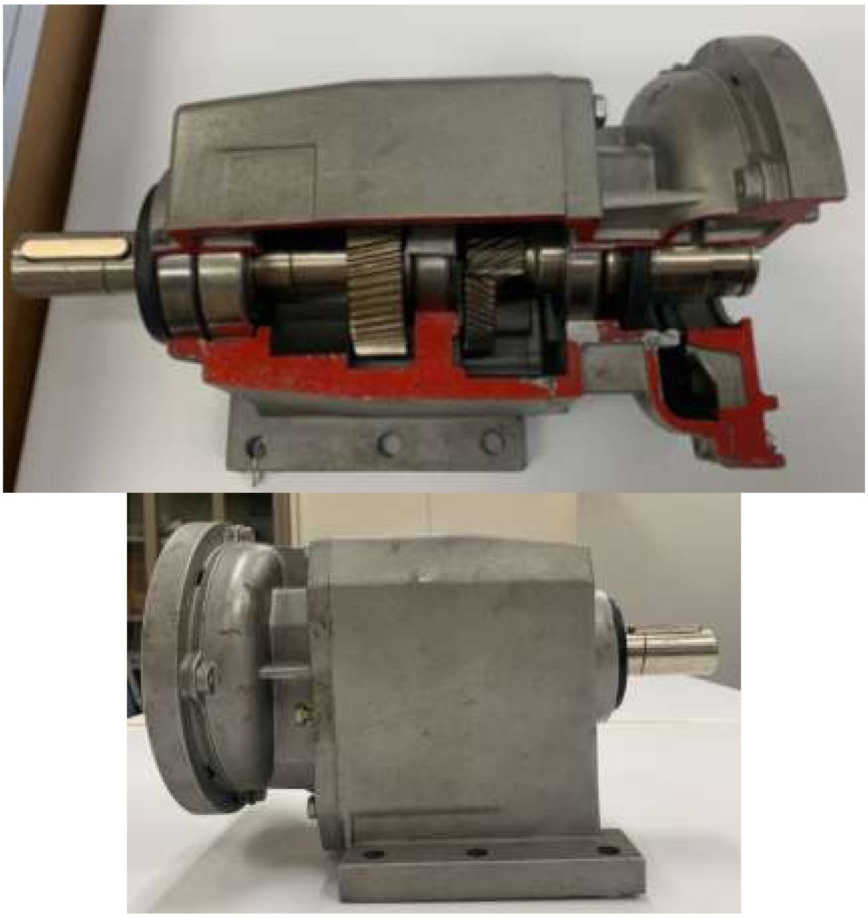


Figure 3 A speed reducer gearbox

4.1.1 Data Collection

Table 8 provides a comprehensive overview of the key components of the gearbox, including their dimensions (length, width, and thickness in the form of XYZ coordinate), mass, material type, and disassembly tools required for each part.

Table 8 Component Details: Dimensions, Mass, Material, Fasteners, and Disassembly Tools of Gearbox

Component	Quantity	Material	Mass [kg]	Dimension [mm]	Types of disassembly tool used
6204 NTN Bearing	1	Chromium steel	0.1	14.00x47.00x47.00mm	Bearing puller
Housing Closure hexagonal with ribs	1	Cast iron	2.67	156.81x79.68x180.32mm	Wrench
6007 NTN Bearing	2	Chromium steel	0.15	14.00x62.00x62.00mm	Bearing puller
Seal 1	1	Plastics - NBR/sintethic rubber	0.01	78.86x6.50x77.62mm	-
6704 NTN Bearing	2	Chromium steel	5.29E-03	4.00x27.00x27.00mm	Bearing puller
Bottom shaft key 17 by 5	1	Steel unalloyed	3.73E-03	7.64x17.00x7.22mm	Key puller, pliers, small hammer
Shaft (1)	1	Steel unalloyed	0.85	47.64x155.00x48.18mm	Hydraulic press
Shaft 1 Gear 1 Key	1	Steel unalloyed	3.23E-03	8.15x16.00x8.15mm	Key puller, pliers, small hammer
Shaft 1 key	1	Steel unalloyed	0.01	0.39x35.27x0.33mm	Key puller, pliers, small hammer
6006 NTN Bearing	2	Chromium steel	0.11	13.00x55.00x55.00mm	Bearing puller
Shaft 2 with helical gear	1	Steel unalloyed	0.68	55.26x110.42x55.90mm	Hydraulic press
Bottom shaft	1	Steel unalloyed	0.17	27.01x70.00x27.01mm	Hydraulic press
Seal 2 for shaft 2	1	Plastics - NBR/sintethic rubber	0.05	61.99x7.00x62.00mm	-
Main housing closure	1	Cast iron	1.78	161.50x32.00x161.49mm	Allen key
Bottom Helical Spur gear	1	Steel low-alloyed	0.28	105.55x15.59x105.55mm	Gear puller, rubber mallet
Bottom shaft key 19	1	Steel unalloyed	4.97E-03	8.10x19.00x8.10mm	Key puller, pliers, small hammer
Main Gear box Housing	1	Steel low-alloyed	9.69	152.00x147.00x174.42mm	-
Bottom helical pinion gear	1	Steel low-alloyed	0.08	50.45x19.08x50.52mm	Gear puller, rubber mallet
Shaft 1 Gear 1	1	Steel unalloyed	0	79.69x22.00x80.85mm	Gear puller, rubber mallet
Allen Bolt	4	Steel unalloyed	2.59E-03	4.84x23.27x7.25mm	Allen key
Housing Closure hexagonal bolt	10	Steel unalloyed	0.01	17.04x25.30x15.41mm	Wrench

The data presented in Table 8 were collected by examining the gearbox. Physical disassembly was not possible due to equipment constraints, but the study used a half-sectioned real *BONFIGLIOLI C202 P P71 SPEED REDUCER GEARBOX* to facilitate data collection. To overcome limitations caused by direct measurement, some engineering-informed assumptions regarding dimensions were made. Section 4.1.3 outlines the theoretical gearbox disassembling process.

4.1.2 Modeling and Assembly

A. Modeling:

Using the dimensions taken during disassembly 3D computer aided design (CAD) models for each part were developed in Solid Edge, a renowned computer aided design (CAD) software tool. 3D CAD models capture dimensions (size, breadth, thickness, and diameter), shape, and functional information for gearbox parts such as housing, shafts, bearings, gears, keys, and seals.

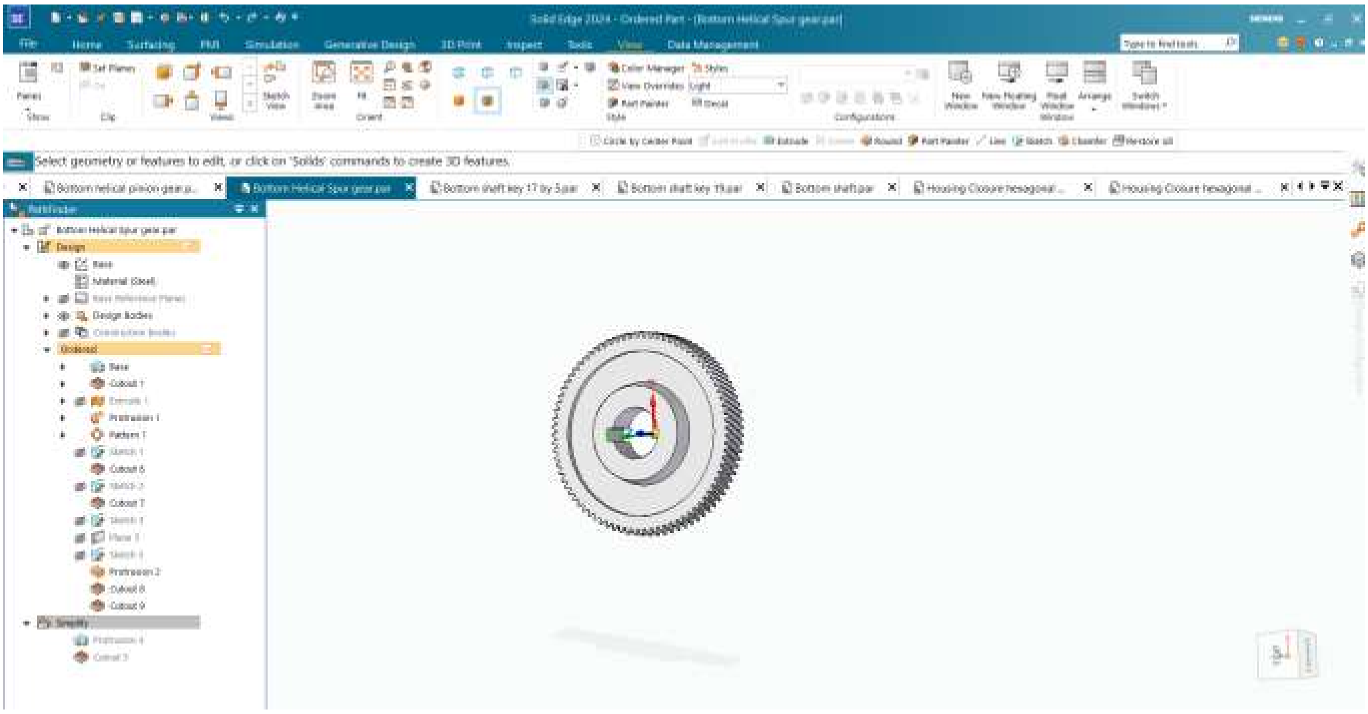


Figure 4 Part Modelling on solid edge 2024

B. Assembly:

Based on the 3D CAD models of the parts designed in Solid Edge, the entire gearbox assembly was assembled virtually. For this purpose, each part i.e., housing, shafts, bearings, gears, keys, and seals was precisely located and oriented in the virtual environment to simulate the actual physical shape of the gearbox. The constraints and relationships were then used to establish proper mating and functionality of the parts, as encountered in real assembly situations. The constructed digital assembly gives a general visualization of the gearbox.

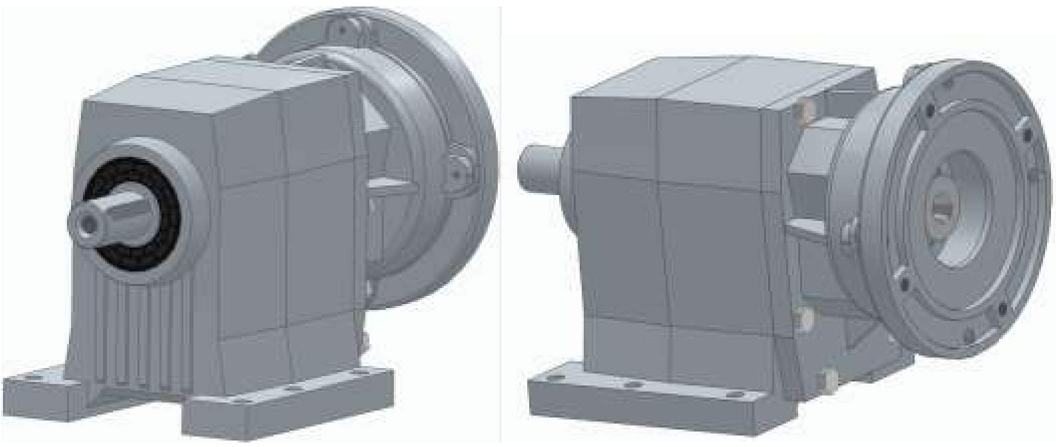


Figure 5 Assembly modelling on solid edge 2024

4.1.3 Disassembly Procedure

Step 1: Flange (Closure of Housing) Removal

Disassembly starts with flange (closure of housing) removal and is located at the most frontal position in the gearbox. Flange is screwed onto the second housing with four Allen bolts.

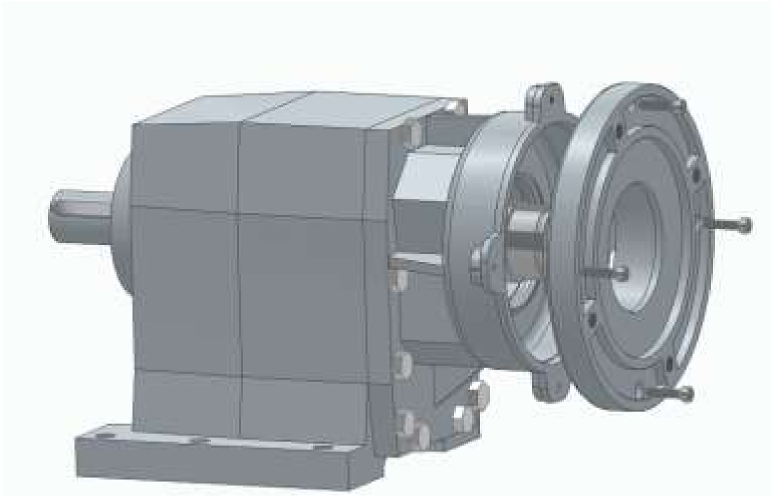


Figure 6 Flange (Closure of Housing) Removal

Step 2: Split the first Housing off the Main Gearbox Housing

The first housing is supported with ribs and joined with ten hex head screws with gearbox housing of the gearbox. It encases its input shaft assembly. Removal includes:

- Using a wrench to loosen and remove all ten hexagonal screws in a crisscross pattern to minimize stress on the structure.
- Dismantling the first housing away from the main gearbox housing
- Observing the position of the input shaft, which remains inside this section, along with its helical spur gear, bearing, and oil seal.

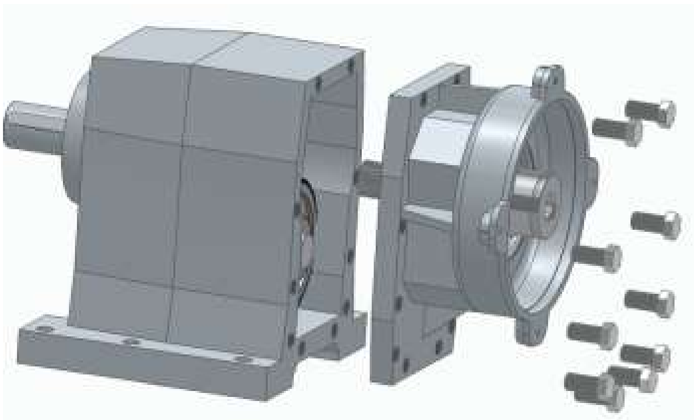


Figure 7 splitting the first Housing off the Main Gearbox Housing

Step 3: Removal of an Input Shaft Assembly

The input shaft is assembled in the first housing and transmits motion downwards to its base helical spur gear. It accommodates a:

- Helical spur gear at one of its ends
- A bearing and an oil seal for supporting and holding in oils
- A helical pinion gear at its other end, whose purpose is to transmit motion to the lower helical spur gear

Disassembly of the Input Shaft Assembly:

The input shaft assembly consists of a helical gear integrally machined at one end of the shaft, along with a bearing and an oil seal. To disassemble the assembly:

- Using a hydraulic press remove the shaft and bearing, ensuring proper alignment to avoid damage to the components.
- The oil seal, being less tightly fitted, can be manually pulled out from the shaft without the need for additional tools.

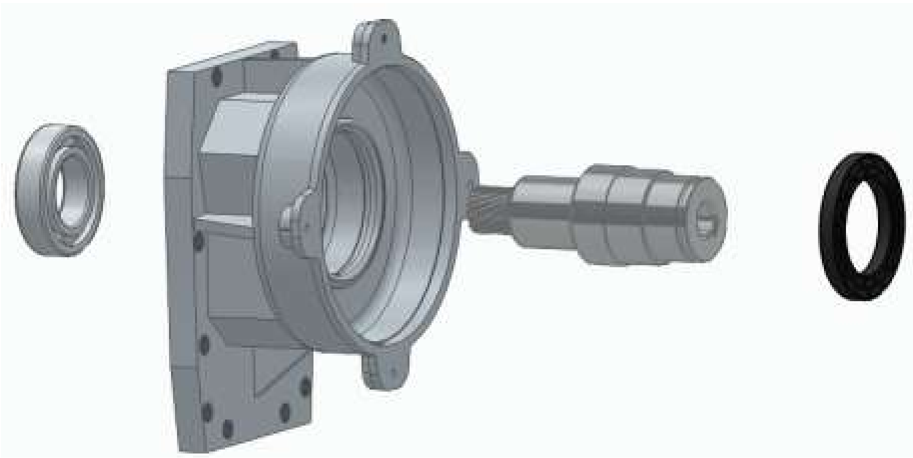


Figure 8 Disassembling an Input Shaft Assembly

Step 4: Extraction of the bottom Shaft Assembly

The bottom shaft assembly is located in the lower section of the gearbox and is mounted within the main gearbox housing. This assembly consists of:

- A **helical spur gear** on the right side, keyed to the shaft, which receives motion from the top helical gear discussed earlier.
- A **helical spur gear** on the left side, which transmits motion to the upper helical gear.

- Two **bearings**:
  - The first bearing is positioned between the two helical gears and is mounted within the main gearbox body to ensure smooth shaft rotation and minimize wear.
  - The second bearing is located beyond the left helical pinion gear, providing additional support and stability.

Disassembly Process:

1. Begin by removing the **helical spur gears** along with their **keys**.
2. Use a **hydraulic press** and **heat application** to extract the shaft, ensuring the helical pinion gear and its key are detached.
3. Finally, remove the **bearings** from their housing using bearing puller.

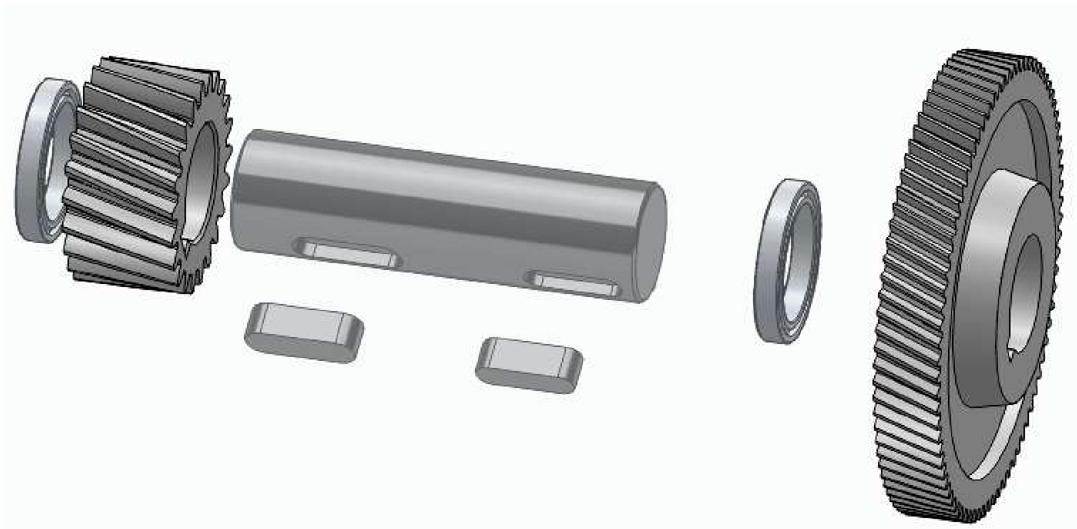


Figure 9 disassembling the bottom Shaft Assembly

Step 5: Exposure of Compositions of a Main Gearbox housing

After the disassembly of a second housing and an input shaft, one will view the inner composition of the housing of a main gearbox. In this part, one will have access to:

- The output shaft, with two bearings and an oil seal
- The top helical spur gear and bottom gear pinion, both keying onto respective shafts

To disassemble such a part:

- The oil seal, being less tightly fitted, and first it can be manually pulled out from the shaft without the need for additional tools.

- Disassembly of a top helical gear, mounted onto a shaft in a housing of a main gearbox
- Extraction of an output shaft, in contact with a bottom gear pinion,
- The two top bearings, with a strong fit in a housing, must have been removed with a press

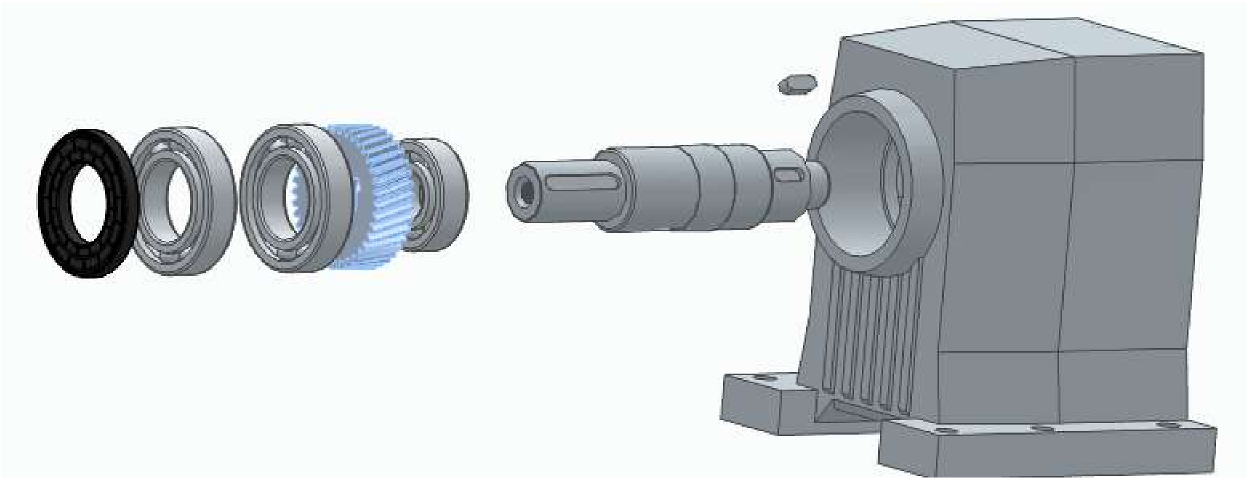


Figure 10 Disassembling of a Main Gearbox housing

4.1.4 Data Analysis and Results

<u>DeSE Analysis</u>

- **Importing into DeSE**:

Importing the assembled gearbox model from Solid Edge into DeSE software. During importing the specific CAD Assembly file should have to be open.

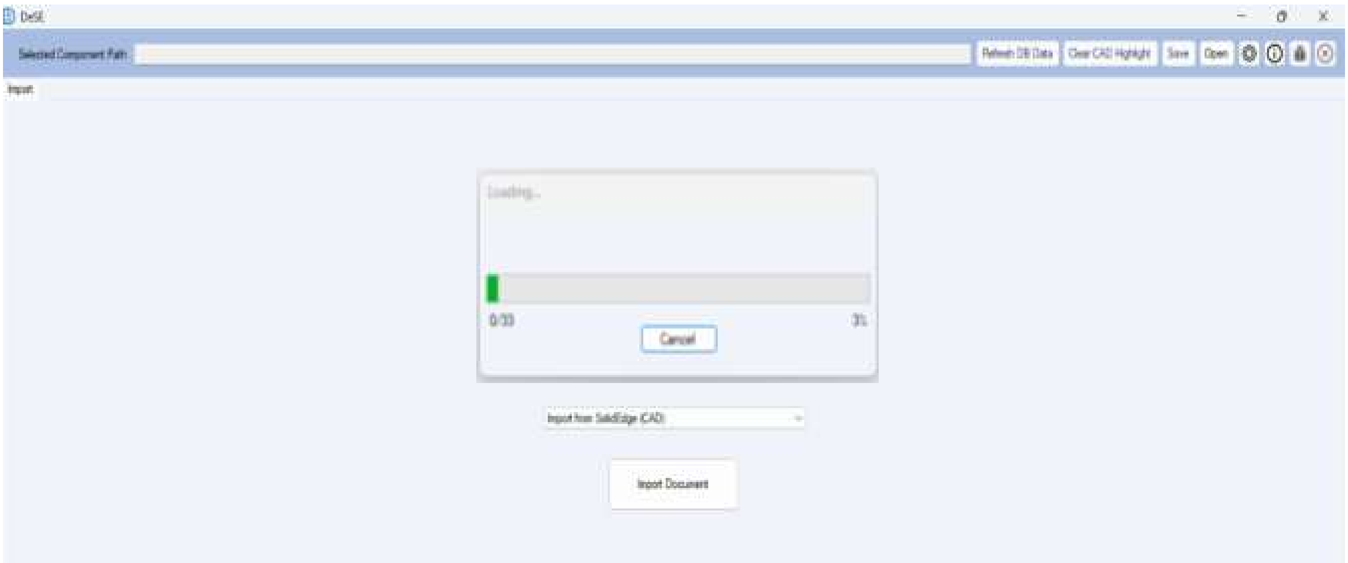
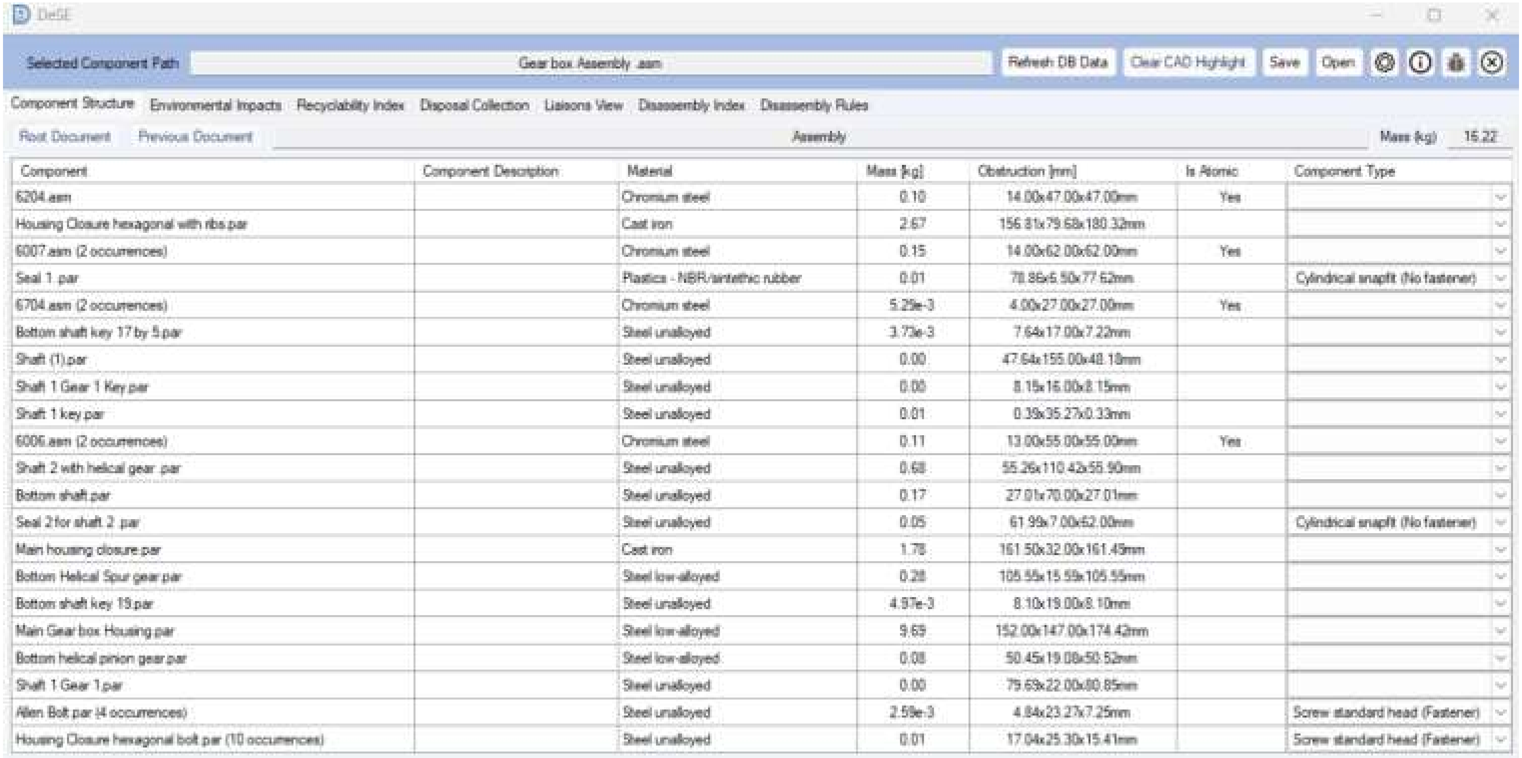


Figure 11 importing the assembled gearbox model from Solid Edge into DeSE software.

- **Component Structure:**

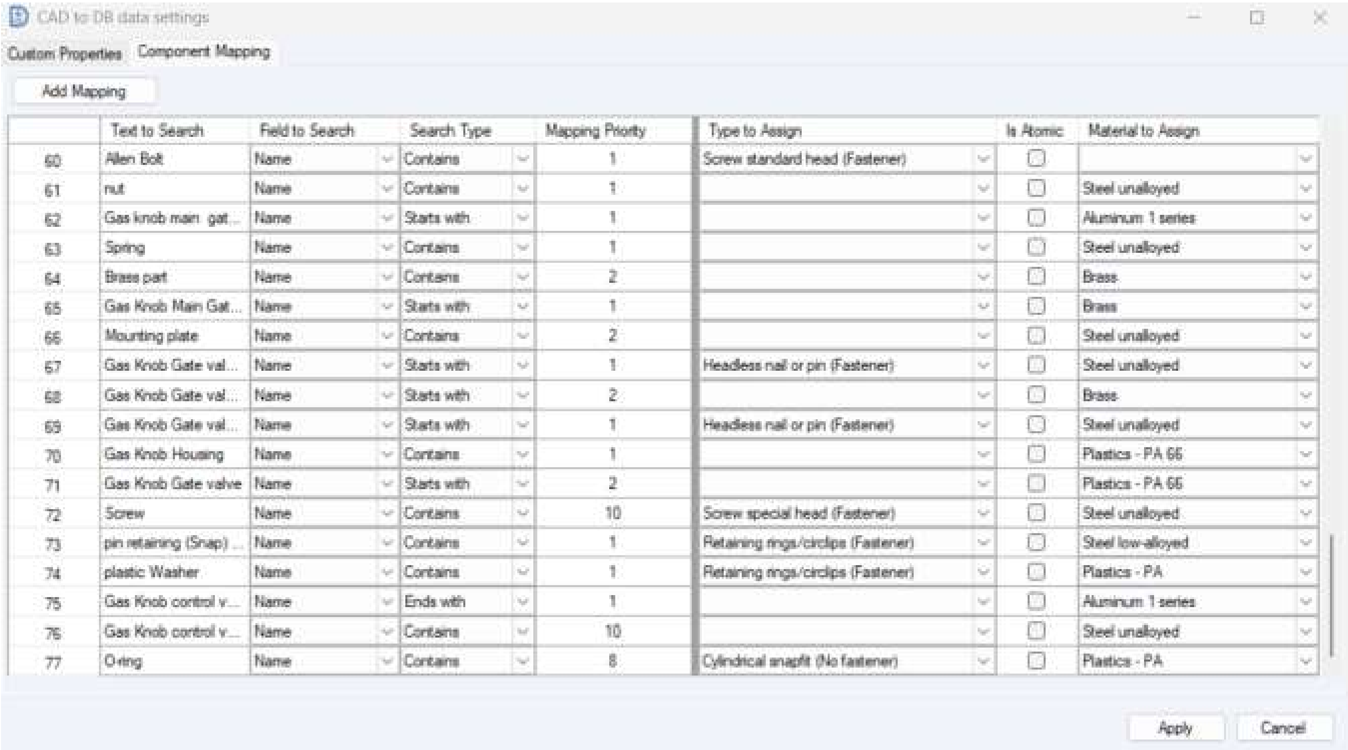
In the Component Structure Tab of the software, the virtual assembly from Solid Edge is imported into the system, where the characteristics of each component as an individual—Component type, part name, material, weight, and dimensions—are carefully inspected and documented. Atomic components, as products that cannot be broken down any further, are identified and grouped based on their functional uses (i.e., fasteners, functional parts, etc.).



Component	Component Description	Material	Mass [kg]	Obstruction [mm]	Is Atomic	Component Type
6204.asm		Chromium steel	0.10	14.00x47.00x47.00mm	Yes	
Housing Closure hexagonal with ribs.par		Cast iron	2.67	156.81x79.68x180.32mm		
6007.asm (2 occurences)		Chromium steel	0.15	14.00x62.00x62.00mm	Yes	
Seal 1 .par		Plastics - NBR/sintethic rubber	0.01	78.86x6.50x77.62mm		Cylindrical snapfit (No fastener)
6704.asm (2 occurences)		Chromium steel	5.29e-3	4.00x27.00x27.00mm	Yes	
Bottom shaft key 17 by 5.par		Steel unalloyed	3.73e-3	7.64x17.00x7.22mm		
Shaft (1).par		Steel unalloyed	0.00	47.64x155.00x48.18mm		
Shaft 1 Gear 1 Key.par		Steel unalloyed	0.00	8.15x16.00x8.15mm		
Shaft 1 key.par		Steel unalloyed	0.01	0.39x35.27x0.33mm		
6006.asm (2 occurences)		Chromium steel	0.11	13.00x55.00x55.00mm	Yes	
Shaft 2 with helical gear .par		Steel unalloyed	0.68	55.26x110.42x55.90mm		
Bottom shaft.par		Steel unalloyed	0.17	27.01x70.00x27.01mm		
Seal 2 for shaft 2 .par		Steel unalloyed	0.05	61.99x7.00x62.00mm		Cylindrical snapfit (No fastener)
Main housing closure.par		Cast iron	1.78	161.50x32.00x161.49mm		
Bottom Helical Spur gear.par		Steel low-alloyed	0.28	105.55x15.59x105.55mm		
Bottom shaft key 19.par		Steel unalloyed	4.97e-3	8.10x19.00x8.10mm		
Main Gear box Housing.par		Steel low-alloyed	9.69	152.00x147.00x174.42mm		
Bottom helical pinion gear.par		Steel low-alloyed	0.08	50.45x19.08x50.52mm		
Shaft 1 Gear 1.par		Steel unalloyed	0.00	79.69x22.00x80.85mm		
Allen Bolt.par (4 occurences)		Steel unalloyed	2.59e-3	4.84x23.27x7.25mm		Screw standard head (Fastener)
Housing Closure hexagonal bolt.par (10 occurences)		Steel unalloyed	0.01	17.04x25.30x15.41mm		Screw standard head (Fastener)

Figure 12 Component Structure Tab of the software

Manual mapping is done for components that are not identified automatically by the software, regarding material type, component type and atomicity.



	Text to Search	Field to Search	Search Type	Mapping Priority	Type to Assign	Is Atomic	Material to Assign
60	Allen Bolt	Name	Contains	1	Screw standard head (Fastener)		
61	nut	Name	Contains	1			Steel unalloyed
62	Gas knob main gat...	Name	Starts with	1			Aluminum 1 series
63	Spring	Name	Contains	1			Steel unalloyed
64	Brass part	Name	Contains	2			Brass
65	Gas Knob Main Gat...	Name	Starts with	1			Brass
66	Mounting plate	Name	Contains	2			Steel unalloyed
67	Gas Knob Gate val...	Name	Starts with	1	Headless nail or pin (Fastener)		Steel unalloyed
68	Gas Knob Gate val...	Name	Starts with	2			Brass
69	Gas Knob Gate val...	Name	Starts with	1	Headless nail or pin (Fastener)		Steel unalloyed
70	Gas Knob Housing	Name	Contains	1			Plastics - PA 66
71	Gas Knob Gate valve	Name	Starts with	2			Plastics - PA 66
72	Screw	Name	Contains	10	Screw special head (Fastener)		Steel unalloyed
73	pin retaining (Snap) ...	Name	Contains	1	Retaining rings/circlips (Fastener)		Steel low-alloyed
74	plastic Washer	Name	Contains	1	Retaining rings/circlips (Fastener)		Plastics - PA
75	Gas Knob control v...	Name	Ends with	1			Aluminum 1 series
76	Gas Knob control v...	Name	Contains	10			Steel unalloyed
77	O-ring	Name	Contains	8	Cylindrical snapfit (No fastener)		Plastics - PA

Figure 13 Component mapping

- **Environmental Impact Analysis**

This tab introduces a specific tool for LCA. Users can enter values for use of a product (power, use duration, life duration), choose end-of-life fate (incineration), and enter country (Italy) in a format allowing location-dependent analysis of information. The tool estimates and shows lifecycle greenhouse gas (GHG) emissions, summed in three phases: Material, Use, and End-of-life.

Table 9 Gearbox Assembly Lifecycle Climate Change Impact for Incineration Scenario

Inputs	Value
Graph Type	Bar Chart
Country	Italy
EoL Strategy	Incineration
Voltage Type	Medium
Power Average [kW]	10
Use Rate [h/year]	2000
Useful Lifetime [years]	10
Preventive Environmental Impact	
Lifecycle Impact	90793.25
Results	
Material Phase	32.18
Use Phase	90760.18
EoL Phase	0.89

Table 10 Gearbox Assembly Environmental Impact Analysis

Material Sub Category	Mass [Kg]	Material Phase [Kg CO2 eq]	EoL Phase [Kg CO2 eq]	Material Sub Category Total[Kg CO2 eq]
Chromium steel	0.63	2.90	0.03	2.93
Cast iron	4.45	8.77	0.24	9.01
Plastics - Sintethic rubber	0.01	0.03	0.03	0.07
Steel unalloyed	1.07	2.27	0.06	2.33
Steel low-alloyed	10.05	18.21	0.53	18.74
Total	16.22	32.18	0.89	33.07

The analysis identifies a dominant environment contribution in "Use Phase" with 99.96% of life cycle contribution at 90,760.18 kg CO2 eq. It reflects that consumption of energy in use of a product is a dominant problem for environment. In contrast, "Material Phase" with a lesser contribution (0.04%) at 32.18 kg CO2 eq, "EoL Phase" holds a negligible contribution (0.001%) with postulated incineration. Steel Low-Alloyed holds a largest contribution in environment with 18.74 kg CO2 eq.

- **Recyclability Index**

The "Recyclability Index" part focuses on measurement of the potential for recyclability of products. Notable characteristics are calculation of different indices of recyclability, such as RBRn (Recyclability Benefit Ratio), Rcyc (Overall Recyclability Index of the product), and Delta (Recyclability Gap, indicating the difference between the theoretical maximum of the product's recyclability and its actual recyclability, and purportedly assessing different aspects of the recyclability of the product). The interface also displays a pie chart of the mass breakdown of the different material groups. A companion table provides detailed information on each material, including recyclability status, mass, and environmental impact factors, thus enabling a general assessment of the product's environmental performance and identifying fields for improvement both in material choice and end-of-life treatment.

Table 11 Gear Box Assembly Recyclability Index Analysis for Incineration Scenario

Field	Value
Indicator	Climate change [kg CO2 eq]
EoL Strategy	Incineration
Recyclability Index Results	
RBRn	0.84
Rcyc	0.85
Delta (%)	99.09

Table 12 Gear Box Assembly Recyclability Index Analysis Results

Material Sub Category	Recyclable?	Mass [kg]	Recyclable Mass [g]	Mass [%]	Dn [kg CO2 eq/kg]	Vn [kg CO2 eq/kg]	Rn [kg CO2 eq/kg]	RCR [kg CO2 eq]	Mn [kg CO2 eq]
Chromium steel	Yes	0.63	0.63	3.88	0.05	4.61	-1.95	0.53	2.9
Cast iron	Yes	4.45	4.45	27.45	0.05	1.97	-1.95	3.78	8.77
Plastics-Synthetic rubber	Yes	0.01	0.01	0.07	3.16	2.84	-1.81	4.40E-03	0.03
Steel unalloyed	Yes	1.07	1.07	6.61	0.05	2.12	-1.95	0.91	2.27
Steel low-alloyed	Yes	10.05	10.05	61.99	0.05	1.81	-1.95	8.54	18.21
Total	Yes	16.22	16.22	100	3.37	13.35	-9.61	13.78	32.18

The results are that the product has excellent recyclability potential, with an Overall Recyclability Index (Rcyc) of 0.85 and a Recyclability Benefit Ratio (RBRn) of 0.84. Moreover, the Delta value, which is the recyclability deficit, is computed at 99.09%, which means that the real recyclability of the product is very close to its theoretical optimum. Analysis of the material composition indicates that the principal elements are low-alloy steel, cast iron, unalloyed steel, and chromium steel, all of which are recyclable types. The highest percentage by mass is from low-alloy steel with 61.99%, followed by 27.45% of cast iron. Environmental impact in terms of climate change (kg CO_2 eq) indicates that steel low-alloyed has the largest cumulative effect at 18.21 kg CO_2 eq, followed by cast iron with an effect of 8.77 kg CO_2 eq. The product's cumulative environmental effect is 32.18 kg CO_2 eq, but the distribution of effects varies by material types. The negative values in some recyclability impact parameters reflect that recycling processes can have positive impacts, leading to the reduction of net emissions.

- **Disposal Collection**

The Component Structure tab provides an overview in terms of material makeup and recyclability distribution across the gearbox assembly. The user can access the recyclability on several levels by selecting either "Category" or "Sub Category" from the pull-down menu. The "Category" level groups materials into more general categories, i.e., steel, cast iron, and plastics, whereas the "Sub Category" level offers another level of classification according to particular material types. Additionally, the user can choose either "Pie Chart" or "Structure Visualization" for visualization to allow for easier intuitive identification of material composition and recyclability of the material in the product.

Table 13 Gear Box Design Disposal Collection Analysis

Sr. No.	Category	Mass (%)	Assembly (%)
1	Cast Iron	4.45	27.45
2	Steel	11.75	72.48
3	Plastics	0.01	0.07

Table 14 Gear Box Design Disposal Collection Analysis Steel materials composition

Sr. No.	Category	Mass (%)	Assembly (%)
2.1	Steel low-alloyed	10.05	61.99
2.2	Steel unalloyed	1.07	6.61
2.3	Chromium steel	0.63	3.88

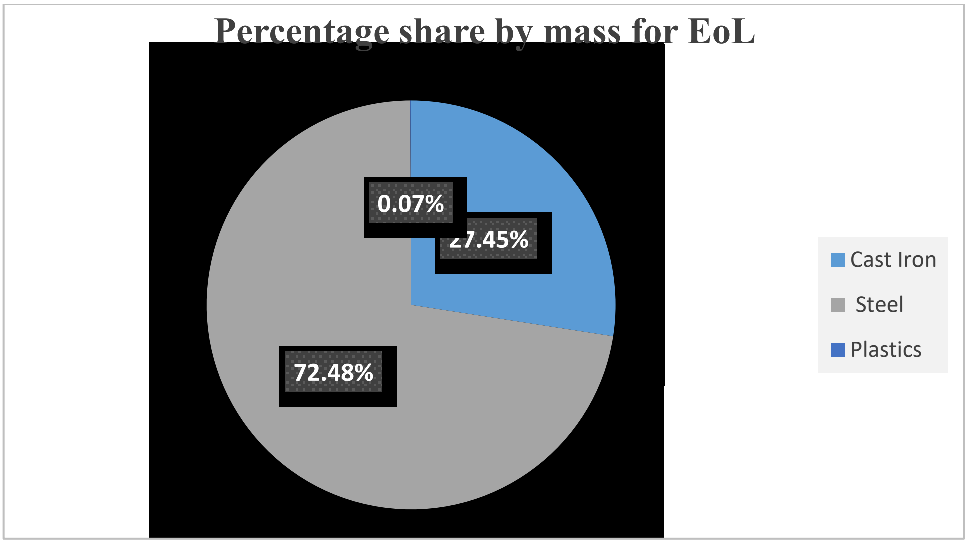


Table 15 Gear Box Design Disposal Collection Analysis

From the findings, the assembly of the gearbox consists mostly of steel with 72.48% of the total mass, followed by cast iron with 27.45%, while plastics occupy a negligible share of 0.07%. Among steel materials, low-alloyed steel constitutes the principal component with 61.99% of the overall assembly, and unalloyed steel accounts for 6.61%. Grey cast iron type 60 is employed in significant structural parts, i.e., the main housing and its closure. The pie chart format clearly shows the predominance of steel and cast iron, pointing to the high potential for recyclability of the gearbox.

- **Liaison Analysis:**

The Liaison View Tab provides a general overview of the association between subassemblies and individual components, aiding in establishing how the various components relate. These associations are fastening techniques, interference fits, and other assembly methods. This stage is significant in determining the assembly structure and the disassembly effort needed.

The interface allows users to manage liaisons by adding, editing, deleting, or merging them. Each row represents a specific liaison, listing the connected components, the number of components involved, the presence and number of fasteners, liaison type, while also indicating whether the liaison was auto-recognized.

This evaluation is a pre-requisite for the second step—the quantification of the Disassembly Index. By looking at the number and nature of liaisons, i.e., joints and fasteners, engineers can quantify disassembly complexity and ascertain areas that can be optimized.

Table 16 Gear box Analysis Liaison analysis

Sr. No.	Components	Number of Components	Number of Fasteners	Liaison Type	Auto Recognized
1	Shaft (1).par:1 + Shaft 1 Gear 1.par:1	2	0	Strong fit interference	No
2	6204.asm:1 + 6007.asm:2 + 6007.asm:3 + Main Gear box Housing.par:1	4	0	Cylindrical snapfit	No
3	Shaft (1).par:1 + Shaft 1 Gear 1 Key.par:1	2	0	Cylindrical snapfit	No
4	Shaft (1).par:1 + Shaft 1 Gear 1 Key.par:1 + Shaft 1 Gear 1.par:1	3	1	Screw standard head	No
5	6006.asm:1 + Shaft 2 with helical gear .par:1	2	0	Weak fit interference	No
6	Housing Closure hexagonal with ribs.par:1 + Main housing closure.par:1	2	0	Integrally threaded part	No
7	Housing Closure hexagonal with ribs.par:1 + Main Gear box Housing.par:1	2	10	Screw standard head	No
8	Housing Closure hexagonal with ribs.par:1 + Main housing closure.par:1	2	4	Screw standard head	No
9	Bottom Helical Spur gear.par:1 + Bottom shaft.par:1	2	0	Strong fit interference	No
10	Bottom shaft key 19.par:1 + Bottom shaft.par:1	2	0	Cylindrical snap fit	No
11	6704.asm:1 + 6704.asm:2 + Bottom shaft.par:1	3	0	Cylindrical snap fit	No
12	Bottom helical pinion gear.par:1 + Shaft 1 Gear 1.par:1	2	0	Strong fit interference	No
13	Shaft 2 with helical gear .par:1 + Bottom Helical Spur gear.par:1	2	0	Strong fit interference	No
14	6204.asm:1 + 6007.asm:2 + 6007.asm:3 + Shaft (1).par:1	4	0	Strong fit interference	No
15	Housing Closure hexagonal with ribs.par:1 + 6006.asm:1	2	0	Strong fit interference	No

16	6704.asm:1 + Bottom shaft.par:1 + 6704.asm:2	3	0	Strong fit interference	No
17	Main Gear box Housing.par:1 + Seal 1 .par:1	2	0	Cylindrical snapfit	No
18	Shaft (1).par:1 + Seal 1 .par:1	2	0	Cylindrical snapfit	No
19	Housing Closure hexagonal with ribs.par:1 + Shaft 2 with helical gear .par:1 + Seal 2 for shaft 2 .par:1	3	0	Cylindrical snapfit	No
20	Shaft 2 with helical gear .par:1 + 6006.asm:1 + Seal 2 for shaft 2 .par:1	3	0	Cylindrical snapfit	No
21	Bottom shaft key 17 by 5.par:1 + 6204.asm:1 + Seal 2 for shaft 2 .par:1	3	0	Cylindrical snapfit	No

Table 16 show that most liaisons are made up of two items, but others have up to four items. Some of the fasteners, for example, bolts, are clearly named for specific connections, for instance, the housing closure assemblies. Importantly, no liaison was generated automatically, i.e., all relationships were defined manually. Color-coded rows identify chosen liaisons, with the individual component interaction in the gearbox assembly being recognizable and editable at will.

- **Disassembly Index Calculation:**

Disassembly Index Analysis tool provides a comprehensive analysis of the disassembly complexity of various components in an assembly. Recyclability can be examined in various levels by selecting "Category" or "Sub Category" from the dropdown list. The analysis is carried out based on the liaison data that was inputted previously, thus making each component's disassembly characteristics well quantified and categorized.

Table 17 Gear Box Assembly *Icom* Results

Disassembly Index	Value
Total	14.6
Min	0.28
Max	1.9
Mean	0.66

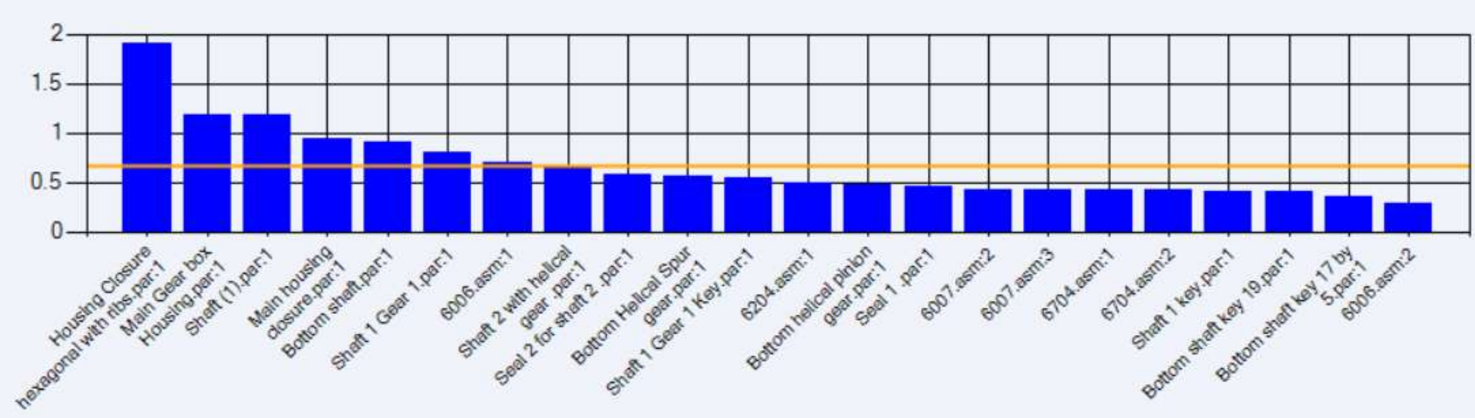


Figure 14 Disassembly Index Calculation and Results

The gearbox design disassembly Index analysis for each of its components is presented in Table 17 below.

Table 18 Gearbox Disassembly Index analysis results

Sr. No.	Component	Ch	Cr	Icom
1	6204.asm:1	0.46	0.52	0.49
2	Housing Closure hexagonal with ribs.par:1	0.64	3.16	1.9
3	6007.asm:2	0.57	0.29	0.43
4	6007.asm:3	0.57	0.29	0.43
5	Seal 1 .par:1	0.55	0.37	0.46
6	6704.asm:1	0.44	0.41	0.42
7	6704.asm:2	0.44	0.41	0.42
8	Bottom shaft key 17 by 5.par:1	0.46	0.25	0.36
9	Shaft (1).par:1	0.52	1.85	1.18
10	Shaft 1 Gear 1 Key.par:1	0.46	0.63	0.54
11	Shaft 1 key.par:1	0.46	0.38	0.42
12	6006.asm:1	0.57	0.83	0.7
13	Shaft 2 with helical gear .par:1	0.57	0.78	0.68
14	Bottom shaft.par:1	0.57	1.24	0.9
15	Seal 2 for shaft 2 .par:1	0.56	0.61	0.59
16	Main housing closure.par:1	0.61	1.29	0.95
17	Bottom Helical Spur gear.par:1	0.55	0.58	0.57
18	Bottom shaft key 19.par:1	0.45	0.38	0.41
19	Main Gear box Housing.par:1	0.79	1.57	1.18
20	Bottom helical pinion gear.par:1	0.57	0.4	0.48
21	Shaft 1 Gear 1.par:1	0.54	1.07	0.81

The Disassembly Index analysis yields a full analysis of disassembly complexity in terms of disassembly effort analysis for individual parts. With a Total Disassembly Index value of **14.60,** overall disassembly effort is represented**. 0.28**, representing least complex part to disassembly, is its minimum value, and **1.90**, representing most complex part to disassembly, is its maximum value, for part Housing Closure Hexagonal with Ribs. With a mean value of **0.66**, the system reflects a moderately complex disassembly level. All these values contribute towards an analysis of a product's ease of processing, maintenance, and recyclability at its life's end.

The graphical analysis yields a deeper analysis of disassembly complexity for individual parts. Shaft 1 Gear 1 Key, Bottom Shaft Key 19, and Bottom Shaft Key 17 by 5 rank amongst most disassembly-intensive parts. Despite relatively small dimensions, positioning and securing in assembly renders them amongst most disassembly-intensive parts, with a high disassembly index value. Other disassembly-intensive parts include high disassembly difficulty parts such as Hexagonal Head Bolt Screw, Housing Closure, and Housing Closure Hexagonal with Ribs, and Main Gear Box Housing. Shaft parts also have a high disassembly index value, with all of them having an Icom value larger than mean value. This is a result of strong interference fit with gears, keys, and bearings, and therefore, proving most disassembly-intensive parts. The contribution of the role played by the fastener cannot go unacknowledged, with its significant contribution towards an increased Icom value (disassembly effort) for shaft part.

Examining the data in Table 9, Housing Closure Hexagonal with Ribs possesses a disassembly difficulty value (*C'r* value) of ***3.16 and an Icom value of 1.9***, and is one of the most disassembly-challenged items, therefore. Likewise, Shaft (1) possesses a disassembly difficulty value (*C'r* value) of ***1.85 and an Icom value of 1.18,*** and its high disassembly difficulty is confirmed yet again. Other disassembly-challenged items include Main Gear Box Housing ***(Icom 1.18***) and Main Housing Closure ***(Icom 0.95).*** On the other hand, Bottom Shaft Key 17 by 5.par:1 possesses relatively less disassembly difficulty, with a disassembly difficulty value (***Cr value) of 0.25*** and an Icom value of 0.36. Nevertheless, even when easier to remove individually, its connectivity with shaft and gear renders overall disassembly difficulty high, with disassembly difficulty value (Cr value) for shaft high, and therefore, its disassembly difficulty varies, with some keys possessing high disassembly difficulty and others easier to remove, with positioning and fixing mechanism a consideration.

Disassembly difficulty for housing and shaft keys is a critical region for improvement in terms of design. That such items have a consistently high removal difficulty value (*C'r* value) and Icom value reveals that increased access and changing fixing mechanism could go a long way in enhancing overall disassembly ease. As such items form part of the assembly structure, redesigning them with alternative fixing techniques and incorporation of modularity could make disassembly easier at no cost for structure integrity.

- **Disassembly rules**

Disassembly Rules Interface allows for the examination of complexity with respect to the disassembly of various components through the setting of a particular disassembly threshold. Here, a threshold value of 1.00 has been utilized, which classifies components as critical, warning-level, or non-critical based on disassembly. Changing the threshold e.g., lowering it to 0.50 would result in a more inclusive and perhaps more detailed examination of disassembly. But a reduced threshold would introduce complexity as well, with additional factors being marked and potential design changes, not all of which might be justified in maximizing disassembly effectiveness. The interface also permits the user to assess recyclability at different levels by selecting either "Category" or "Subcategory" from the pull-down menu, permitting a more thorough analysis of disassembly and material recovery potential.

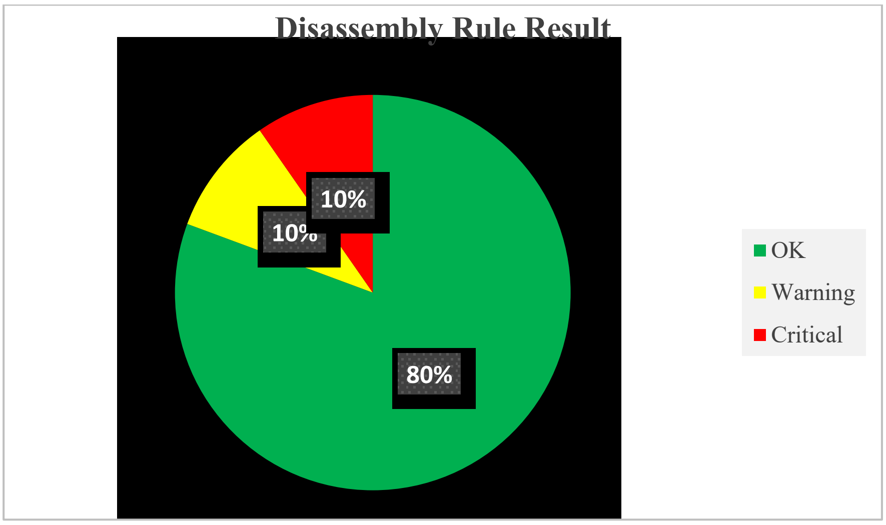


Figure 15 Gear Box Disassembly Rules

The disassembly rule results give a close examination of each component disassembly attempt as OK, Warning, or Critical. Certain of the components, such as Bearing 6204 and 6007, and bolts, are of OK type, that is, they are within the limit of acceptable disassembly threshold. However, components such as Housing Closure Hexagonal with Ribs and Main Gear Box Housing are classified as Critical due to the high number of fasteners used, which makes it difficult to disassemble. Additionally, shaft components and keys are given a Warning rating since they are subject to huge fit interference, which makes it difficult to pull them out. Components requiring extensive tooling or involving more than the specified limit of disassembly operations are also rated. This research points out some of the areas where design changes like reducing the number of fasteners, improving accessibility, or changing fixing mechanisms would improve disassembly efficiency and facilitate maintenance.

4.1.5 REDESIGN

4.1.5.1 Redesign of Housing Connections

The disassembly analysis of the first gearbox design showed that the use of high number of fasteners is a considerable issue, seen in Figure 20 of this document and supported by output generated from DeSE software. To make improvements, specific efforts focused on minimizing and optimizing the connection between the secondary housing and the primary gearbox housing, featuring a hexagonal shape supported with a rib and used as a driving shaft housing.

The two housings in the first were joined with 10 hexagonal bolts, creating a high level of complexity in both disassembly and assembly operations. To make improvements in terms of efficiency and ease in disassembly, the redesign reduces the number of bolts used to join the two main housing seen in figure 20 by 50%, and five of them alone will be present in its stead. To make improvements in terms of ease in the assembly process and a reduced use of traditional fasteners, a mechanism of snap-fit is included in its place for five of the traditional five bolts.

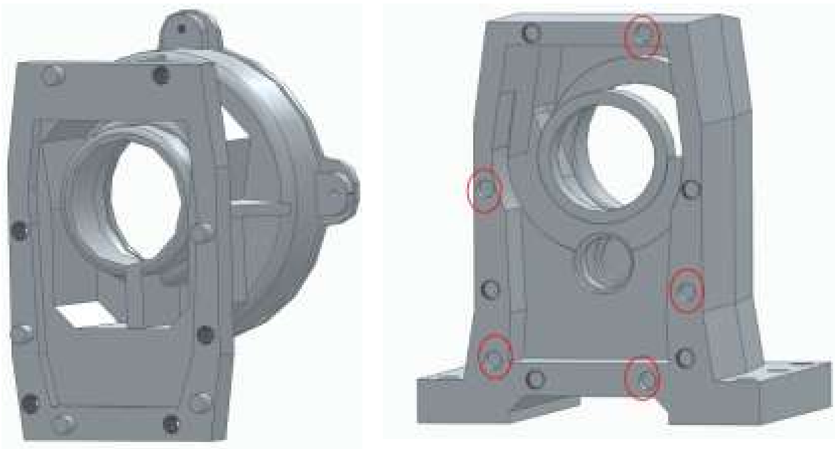


Figure 16 Redesigned gearbox housing

4.1.5.2 Redesign of Shaft, Gear, and Key Connections

The initial gearbox design included a strong interference fit for connecting shaft, gear, and key. In its configuration, a high *Icom* is shown. The strong interference fit made disassembly challenging and often led to potential damage to the components due to excessive tightness between them. Dismantling gear from shaft involved a necessity for a hydraulic press, an arrangement that not only increased labor intensity but posed a danger of damaging parts during disassembly.

To improve such component assembly, redesign seeks to use a traditional key-shaft-gear assembly with a spline mechanism that creates a linkage between shaft and gear. With such an alternative connectivity, both assembly and disassembly processes become easier through even distribution of loads and creation of a strong linkage with a reduced chance of failure during disassembly. Unlike an interference fit, whose effectiveness in torque transmission is a function of high contact pressure, a spline mechanism works through numerous contact interfaces. By having many contact points, such a configuration reduces areas of high stress concentrations and overall promotes durability in parts.

The use of a spline connection eliminates press-fit assembly requirements, and therefore, reduces installation and both assembly and disassembly force requirements. By minimizing such requirements, redesign addresses part deformation and wear concerns, concerns that, in the current model, are heightened through high force requirements of an interference fit. In addition, redesign promotes accuracy in positioning parts, and in the process, reduces disassembly failure probability through misalignment, and at the same time, raises efficiency in gearbox operations during use.

The integration of a spline mechanism creates a high level of cohesion in the gearbox, enhancing mechanical efficiency and ease of maintenance access. Reduced disassembly work helps promote maintenance operations with less downtime, and its purpose is to enhance system reliability and maximize operational life span. With technology improvement through redesign, a strong and efficient gearbox with high transmission in loads and ease in disassembly and assembling processes is attained.

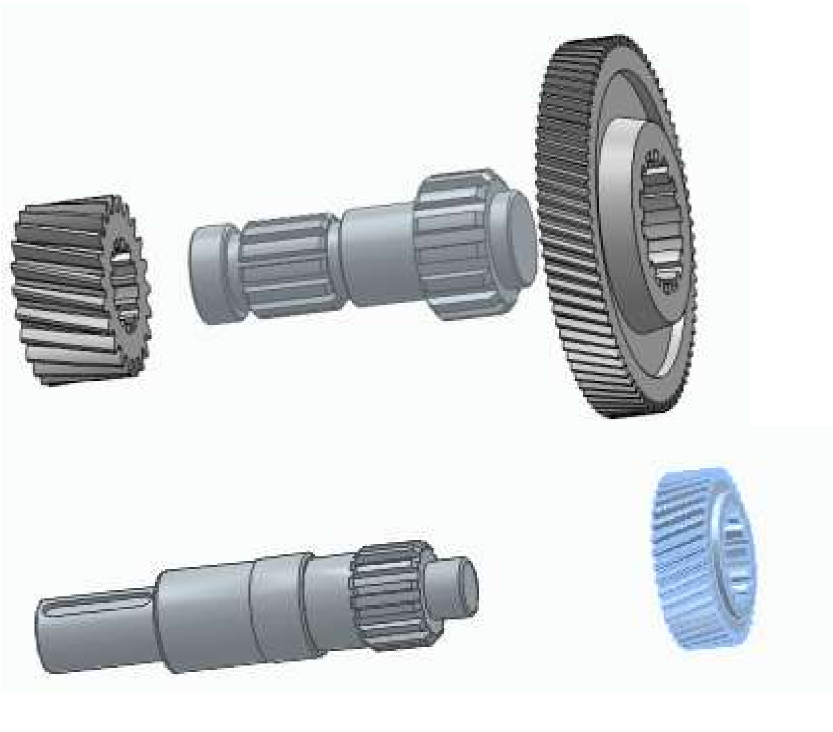


Figure 17 Redesigned gearbox shafts and gears

4.1.5.3 Redesign Data Analysis

This Environmental Impact Analysis considers greenhouse gas emissions (in terms of kg CO_2 equivalent, abbreviated kg CO_2 eq) for reengineering a gearbox assembly located in Italy. Analysis involves three phases in a lifecycle: Material, Use, and EoL. Cumulative lifecycle impact totals 90,793.20 kg CO_2 equivalent, with most (90,760.18 kg CO_2 equivalent) during the Use Phase, then during the Material Phase (32.13 kg CO_2 equivalent), and least during EoL (0.89 kg CO_2 equivalent). High impact during use is owed in most part to a 10 kW consumption over 2,000 working hours per annum for ten years.

The impact for the Material Phase comes almost exclusively from steel alloys such as low-alloyed steel (18.74 kg CO_2 equivalent), cast iron (9.09 kg CO_2 equivalent), and unalloyed steel (2.19 kg CO_2 equivalent). For EoL, negligible impact (0.89 kg CO_2 equivalent) reflects low emissions for disposal. High impact during use reflects a strong case for increased efficiency and minimizing consumption in a gearbox contributing to a significant role in lessening environment repercussions, and therefore redesign activity in such an area could form a key target for future activity.

Table 19 Redesigned Gearbox Assembly Lifecycle Climate Change Impact for Incineration Scenario

Inputs	Value
Graph Type	Bar Chart
Country	Italy
EoL Strategy	Incineration
Voltage Type	Medium
Power Average [kW]	10
Use Rate [h/year]	2000
Useful Lifetime [years]	10
Preventive Environmental Impact	
Lifecycle Impact	90793.20
Results	
Material Phase	32.13
Use Phase	90760.18
EoL Phase	0.89

Table 20 Redesigned Gearbox Assembly Environmental Impact Analysis

Material Sub Category	Mass [Kg]	Material Phase [Kg CO2 eq]	EoL Phase [Kg CO2 eq]	Material Sub Category Total[Kg CO2 eq]
Cast iron	4.49	8.86	0.24	9.09
Chromium steel	0.63	2.90	0.03	2.93
Plastics - Sintethic rubber	0.01	0.03	0.03	0.07
Steel low-alloyed	10.05	18.21	0.53	18.74
Steel unalloyed	1.01	2.13	0.05	2.19
Total	16.19	32.13	0.89	33.02

For the redesigned gearbox assembly, the recyclability indices remain high (RBRn = 0.84, Rcyc = 0.85, Delta = 99.10%), indicating strong material recovery potential. The material distribution prioritizes steel alloys and cast iron, ensuring durability while maintaining recyclability. Chromium steel and unalloyed steel contribute minimally but remain fully recyclable. The use of plastics/synthetic rubber is minimal (0.07%), reducing environmental impact.

Table 21 Redesigned Gear Box Assembly Recyclability Index Analysis for Incineration Scenario

Field	Value
Indicator	Climate change [kg CO2 eq]
EoL Strategy	Incineration
Recyclability Index Results	
RBRn	0.84
Rcyc	0.85
Delta (%)	99.10

Table 22 Redesigned Gear Box Assembly Recyclability Index Analysis Results

Material Sub Category	Recyclable?	Mass [kg]	Recyclable Mass [g]	Mass [%]	Dn [kg CO2 eq/kg]	Vn [kg CO2 eq/kg]	Rn [kg CO2 eq/kg]	RCR [kg CO2 eq]	Mn [kg CO2 eq]
Chromium steel	Yes	0.63	0.63	3.88	0.05	4.61	-1.95	0.53	2.90
Plastics - Sintethic rubber	Yes	0.01	0.01	0.07	3.16	2.84	-1.81	4.40e-3	0.03
Steel unalloyed	Yes	1.01	1.01	6.22	0.05	2.12	-1.95	0.86	2.13
Cast iron	Yes	4.49	4.49	27.75	0.05	1.97	-1.95	3.82	8.86
Steel low-alloyed	Yes	10.05	10.05	62.08	0.05	1.81	-1.95	8.55	18.21
Total	Yes	16.19	16.19	100	3.37	13.35	-9.61	13.76	32.13

The redesign of the gearbox has translated into improvements in terms of disassembly effort, with recently developed metrics for the *Icom* providing an evidence base for the improvements. Overall value for disassembly has been reduced to 9.88, with an average value of 0.55, signifying a general improvement in disassembly ease. In addition, individual parts' criticality has been optimized, with a drop in peak *Icom* values from 1.06 to a balanced distribution in terms of parts' criticality.

A significant improvement involves the housing with a hexagonal rib, whose initial high *Icom* value of 1.06 arose from its fastening mechanism. In redesign, the use of fasteners has been reduced and a snap-fit mechanism included, effectively lowering disassembly related difficulty. Similarly, the base gearbox housing, that's initial high demand for effort arisen from high-fit interference, has been redesign for easier access, as reflected in its reduced criticality rating.

Table 23 Redesigned Gear Box Assembly *Icom* Results

Disassembly Index	Value
Total	14.6
Min	0.28
Max	1.9
Mean	0.66

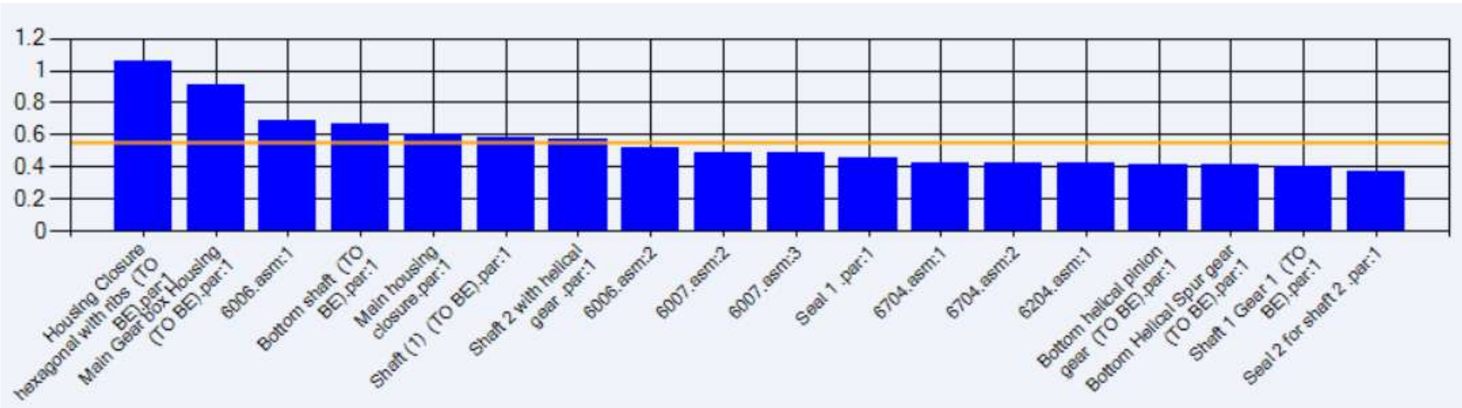


Figure 18 Disassembly index result for redesigned gearbox assembly

The shaft and gear interface, whose disassembly was initially inconvenient due to high-fit interference, have been redesigned through replacement of key connection with a mechanism of a spline. Through redesign, *Icom* values for both shaft (1) from to and for the lower shaft parts have reduced, allowing them to be removed with much ease. In addition, reduced use of new connecting mechanism has reduced disassembly requirements for a hydraulic press, whose use initially restricted maintenance operations.

Table 24 Disassembly index result for redesigned gearbox assembly

Component	*Ch*	*Cr*	*Icom*
Shaft 2 with helical gear .par:1	0.57	0.58	0.58
Shaft 1 Gear 1 (TO BE).par:1	0.54	0.26	0.4
Shaft (1) (TO BE).par:1	0.52	0.64	0.58
Seal 2 for shaft 2 .par:1	0.56	0.18	0.37
Seal 1 .par:1	0.55	0.37	0.46
Main housing closure.par:1	0.61	0.6	0.6
Main Gear box Housing (TO BE).par:1	0.79	1.03	0.91
Housing Closure hexagonal with ribs (TO BE).par:1	0.64	1.47	1.06
Bottom shaft (TO BE).par:1	0.56	0.78	0.67
Bottom Helical Spur gear (TO BE).par:1	0.56	0.26	0.41
Bottom helical pinion gear (TO BE).par:1	0.57	0.26	0.41
6704.asm:2	0.44	0.41	0.42
6704.asm:1	0.44	0.41	0.42
6204.asm:1	0.46	0.38	0.42
6007.asm:3	0.57	0.4	0.48
6007.asm:2	0.57	0.4	0.48
6006.asm:2	0.57	0.48	0.52
6006.asm:1	0.57	0.8	0.68

Furthermore, the rule-based analysis indicates that several critical components, such as the main gearbox housing and housing closure hexagonal bolt, were initially flagged for requiring excessive effort for removal. After the redesign, these elements no longer exceed the chosen threshold, demonstrating the success of the modifications. The optimization has particularly improved the fastener distribution, reducing unnecessary bolts while maintaining structural integrity. The warning for the main gearbox housing's critical mass rating (1.00) highlights the importance of weight distribution in future iterations, but overall, the redesign has achieved a quantifiable reduction in disassembly complexity and effort required for maintenance.

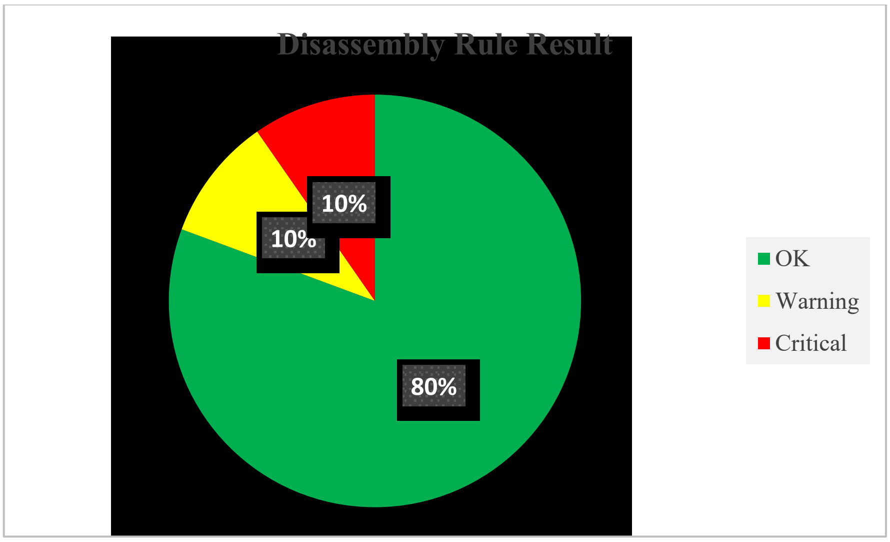


Table 25 Disassembly index result for redesigned gearbox assembly

4.2 Gas knob

The gas knob assembly is a critical component of gas-run appliances like ovens and stoves. The assembly usually consists of a rotating knob, a control shaft, and a valve mechanism. The knob, which is usually plastic or metallic, facilitates control of the flow of gas. The rotational motion of the knob is transferred to the valve assembly by the control shaft, which regulates the flow of gas to the appliance's burner. The assembly also features safety devices intended to prevent accidental gas escape, i.e., interlocking devices and spring-loaded valves.

Figure 19 Gas knob (Gas control valve)

4.2.1 Data Collection

Table X provides a comprehensive overview of the key components of the Gas knob (Gas control valve), including their dimensions (length, width, and thickness in the form of XYZ coordinate), mass, material type, and disassembly tools required for each part.

Table 26 Component Details: Dimensions, Mass, Material, Fasteners, and Disassembly Tools of Gas knob

Sr. no.	Component	Material	Mass [kg]	Obstruction [mm]	Is Atomic	Component Type
1	**Gas knob Gate valve.asm**	Assembly	0.19	105.09x57.85x57.83mm	No	
1.1	Gas knob blue seal for main gate valve.par	Plastics - NBR/ sintethic rubber	3.96E-04	13.67x13.82x6.32mm		Cylindrical snapfit (No fastener)
1.2	Gas knob main gate valve.par	Aluminum 1 series	1.00E-01	65.08x39.00x36.76mm		
1.3	Gas Knob Gate valve Internal Compression spring 8.5D.par	Steel unalloyed	6.04E-04	15.85x13.22x13.22mm		
1.4	Gas Knob Main Gate valve closure.par	Unknown material (Aluminum 1 series)	4.70E-03	14.00x18.00x18.00mm		
1.5	Gas Knob Gate valve screw (brass).par	Plastics - PA 66	9.89E-05	7.20x5.47x5.56mm		Screw special head (Fastener)
1.6	Gas knob Control valve.asm	Assembly	0.01	16.53x16.53x52.76mm	No	
1.7	Gas Knob Gate valve closure seal (O-ring red).par	Plastics - PA 66	1.19E-04	1.50x20.95x20.95mm		Cylindrical snapfit (No fastener)
1.8	Gas Knob Gate valve Mounting plate.par	Steel unalloyed	0.02	13.13x57.85x52.71mm		
1.9	Gas Knob Gate valve Mounting plate screw M2.5x0.35.par (3 occurrences)	Steel unalloyed	4.28E-04	10.42x5.31x5.31mm		Screw special head (Fastener)
1.10	Gas knob Gate and control valve top closure plate.asm	Steel unalloyed	0.02	78.88x33.98x96.70mm	No	
1.11	Gas Knob Gate valve Internal Compression spring 0.75D.par	Steel unalloyed	7.05E-04	14.25x16.64x16.64mm		
1.12	Gas Knob Gate valve Compression spring .par	Steel unalloyed	3.82E-04	11.61x15.49x15.49mm		
1.13	Gas Knob Gate valve Brass part .par	Brass	0.02	22.34x17.00x17.00mm		
2	**Gas knob Top Housing .asm**	Assembly	0.04	79.64x79.48x199.82mm	No	
2.1	Gas Knob Gate valve top pin for holding (no round edge) .par	Steel unalloyed	2.45E-04	2.00x10.00x2.00mm		Headless nail or pin (Fastener)
2.2	Gas Knob Housing.par	Plastics - PA 66	0.02	79.64x79.48x39.50mm		
2.3	Gas Knob Gate valve 2 pin for holding .par	Steel unalloyed	2.43E-04	2.00x10.00x2.00mm		Headless nail or pin (Fastener)
2.4	Gas Knob Gate valve .par	Plastics - PA 66	0.01	49.00x46.25x9.02mm		

2.5	Gas Knob Gate valve tip 2 pin for holder .par	Brass	7.16E-03	8.00x8.00x32.00mm		
3	**Gas knob switch.asm**	Assembly	0.00551	42.30x10.04x23.51mm	No	
3.1	Gas Knob gate valve switch (Black part).par	Plastics - PA 66	2.86E-03	29.38x10.02x16.00mm		
3.2	Gas Knob gate valve switch Tamper.par	Plastics - PA 66	5.74E-05	3.00x4.00x4.00mm		
3.3	Gas Knob gate valve switch.par	Plastics - PA 66	1.02E-03	29.38x3.02x16.00mm		
3.4	Gas Knob gate valve switch Brass part 1 top.par	Brass	9.40E-04	16.30x6.50x6.01mm		
3.5	Gas Knob gate valve switch Brass part 2 Bottom.par	Brass	6.39E-04	12.62x6.50x2.41mm		
4	**Gas Knob Gate valve Mounting plate screw M2.5x0.35.par (3 occurrences)**	Steel unalloyed	4.28E-04	5.18x5.18x10.42mm		Screw special head (Fastener)
5	**Gas knob Gate and control valve top closure plate.asm**	Steel unalloyed	2.00E-02	78.88x33.98x96.70mm	No	
5.1	Gas Knob Gate valve Mounting plate top.par	Steel unalloyed	0.01	38.00x27.62x19.00mm		
5.2	Gas knob Screw pin for main gate valve.par	Steel unalloyed	2.67E-03	8.84x8.82x18.00mm		Screw special head (Fastener)
5.3	Gas Knob Gate valve Mounting plate cup for closure.par	Steel unalloyed	3.32E-03	19.81x19.81x4.76mm		
5.4	Gas Knob Gate valve Mounting plate top nut for pin screw .par	Steel unalloyed	2.01E-03	14.69x14.68x6.31mm		Screw special head (Fastener)

The data presented in Table 10 were collected by examining the gas knob. The measurement is directly taken after disassembling each components of DEFENDI Gas knob (Gas control valve). Section 4.2.3 outlines the Gas knob (Gas control valve) disassembling process.

4.2.2 Modeling and Assembly

a) Modeling:

The gas knob assembly consists of several parts, as indicated by the numbered parts, such as the knob housing, control shaft, valve body, seals (e.g., O-rings), springs, and internal parts such as the switch and tamper. All these parts work together to regulate the appliance's gas supply, thus enabling controlled and safe use. Individual 3D CAD models of each part were created from the measurements obtained while performing the disassembly exercise. The models, which have been designed on Solid Edge software, reflect the unique geometry and features of each component, including operating information, shape, and size.

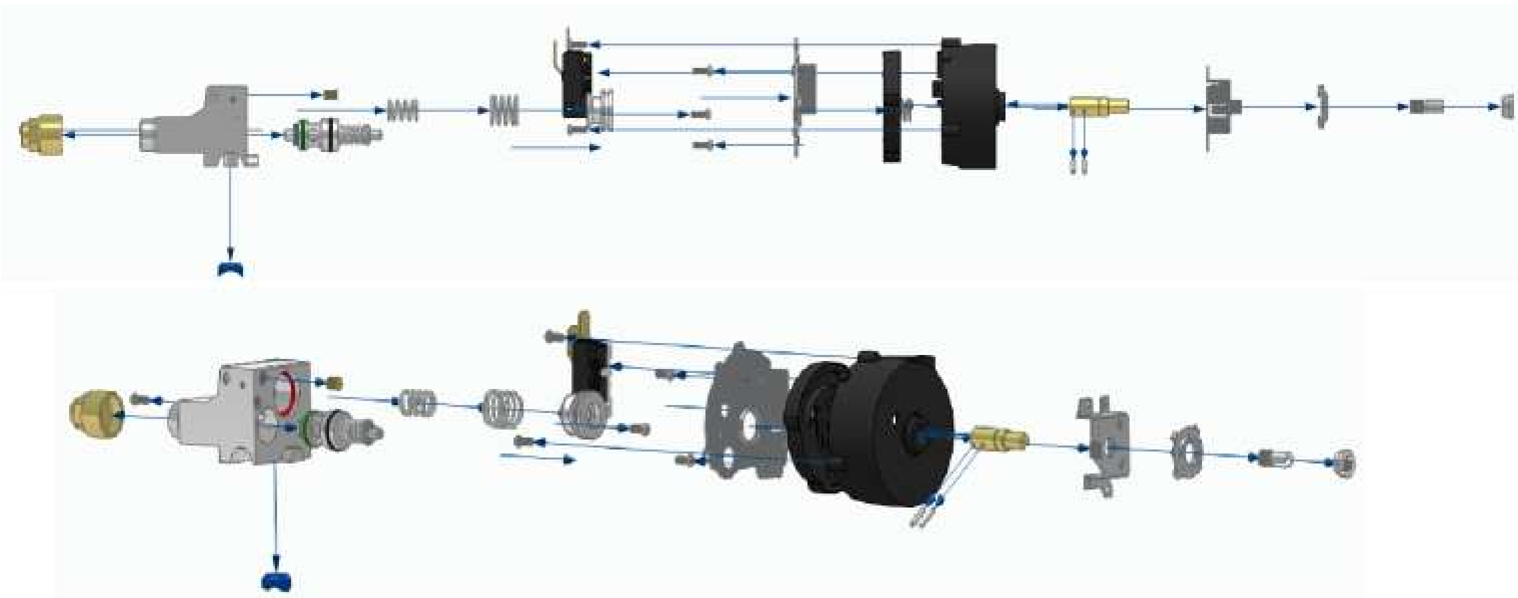


Figure 20 Exploded view of Gas knob 3D Modeling

b) Assembly:

Using the 3D CAD models of every one of the individual components (knob housing, control shaft, valve body, seals, springs, internal mechanisms, etc.), the entire gas knob assembly was assembled virtually in Solid Edge. Each component was precisely placed and positioned in the virtual world to replicate the actual physical configuration within the gas knob. The part-to-part relationships and constraints, such as mating surfaces, clearances, and interferences, were defined to enable proper assembly and functioning, simulating real-world assembly operation. The digital assembly thus developed provides a graphical representation of the gas knob assembly and can be utilized as a platform for future analyses, including kinematic simulation and interference analysis.

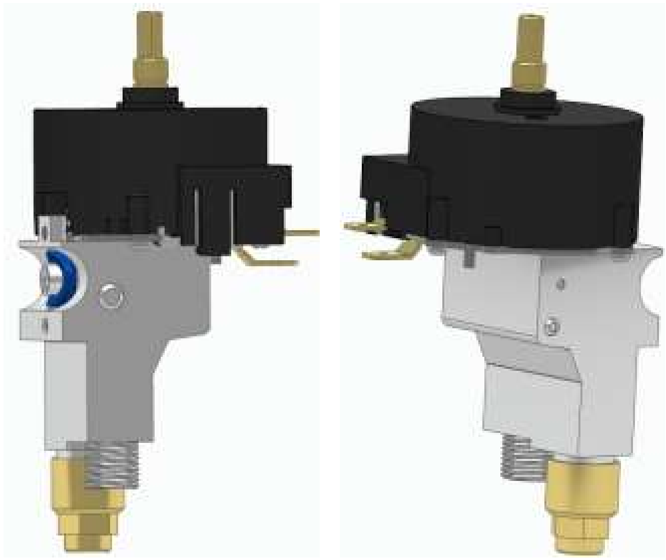


Figure 21 Gas knob Assembly model

4.2.3 Disassembly Procedure

Step-1 Disassembling the Gas knob top housing

The disassembly begins by removing the black plastic top housing assembly. This is done by loosening and removing three screws holding it in place to the mounting plate fixed to the main gate valve assembly.

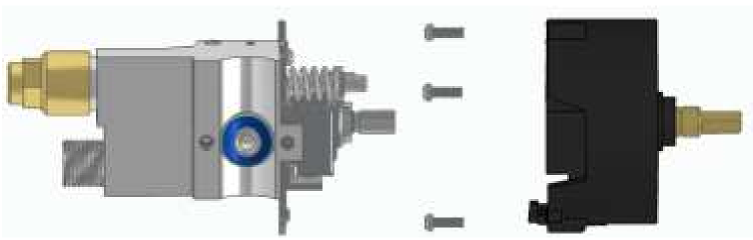


Figure 22 Disassembling the Gas knob top housing

The top housing sub-assembly, i.e., the gas knob switch with tamper, the primary gas knob housing (black plastic), the gas knob gate valve guide, and the gate valve brass pin shaft, was next removed. The gas knob switch is held to the housing in a snap-fit, removable with little force. The guide for the gate valve gas knob is attached in a manner that it can be loosened when the sub-assembly is being removed from the main gate valve mounting, making it easy to remove. The brass component is fitted into the housing with two pins. While it is easy to remove the gate valve guide, the removal of the brass component from the housing is a design problem since it is tightly fitted, and this can negatively impact the ease of disassemble. This is an area that can be improved in subsequent releases to benefit DfD. A virtual representation of such a disassembly is depicted in Figure 24.

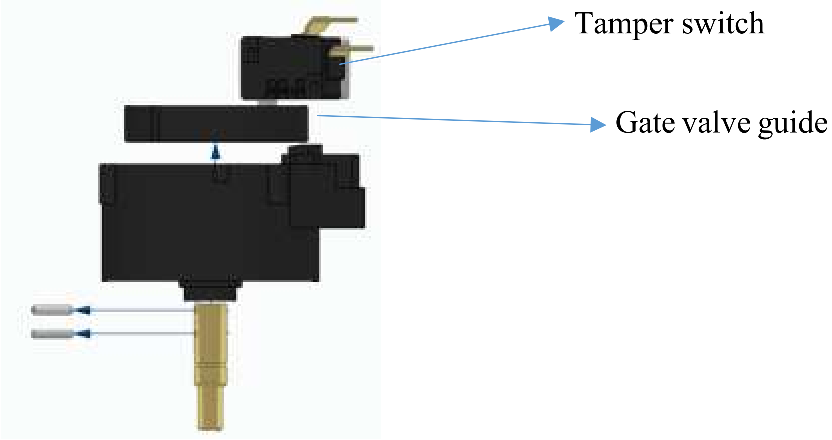


Figure 23 Gas Knob top housing sub-assembly

Step-2 Gas knob gate and control valve disassembly

Disassembly begins with the removal of the gas knob gate and control valve sub-assembly from the mounting plate by loosening two screws. This exposes a compression spring, which becomes relaxed upon loosening of the screws. Further disassembly of the sub-assembly is the removal of the adjustment nut and screw, which is used to regulate gas flow when the appliance is in use. This nut is strongly fitted to a circular plate, which forms the bottom piece for the parts of the sub-assembly. This circular plate is joined by a hinge (formed by folding the edge of the plate on four sides) to the last base plate the mounting plate that fastens the whole assembly to the appliance.

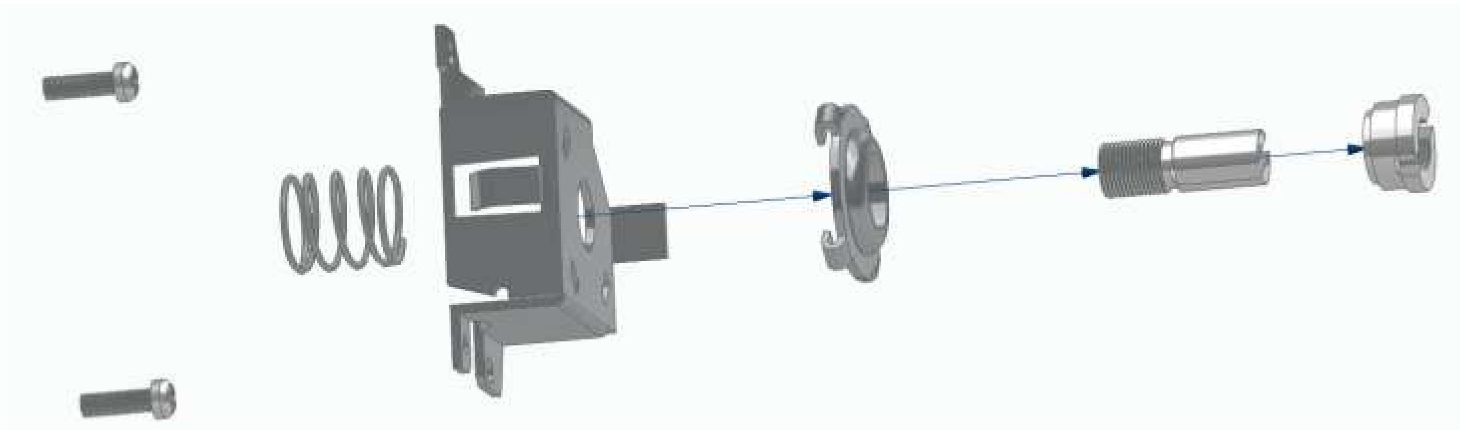
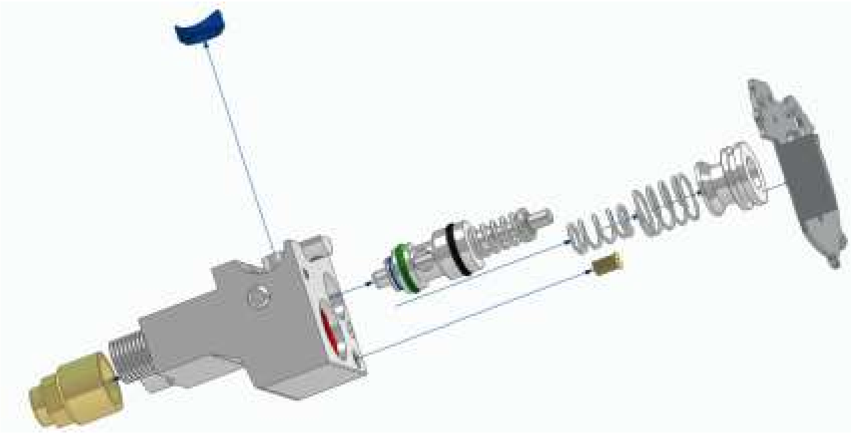


Figure 24 Gas knob gate and control valve sub-assembly

Step-3 Gas knob main gate valve disassembly

Disassembly starts with the removal of the mounting plate. The screws were already removed while disassembling the gas knob gate and control valve sub-assembly. After removing the mounting plate, the main gate valve closure, aluminum with O-rings, is removed by two compression springs, so it is readily ejected from the main gate valve housing. Likewise, the gas control valve can be pulled out, but a little more force from the hands is necessary.



(a)

(b)

Figure 25 Gas knob main gate valve disassembly (a) virtual (b) Actual object

Step-4 Gas knob control valve disassembly

The gas knob gate valve assembly has a pin shaft with snap rings on the right-hand end that hold the washer support and spring. The control valve is made of aluminum and has the shaft passing through it, with two O-rings (green and black) for the prevention of gas leakage when assembled with the main gate valve body. A plastic washer and cap are pressed onto the left end of the shaft pin. Disassembly begins by removing the retaining ring, for which special pliers or an equivalent tool designed for the removal of retaining rings are required. With the retaining ring off, the washer and spring can be removed from the pin shaft with ease. The aluminum control valve can also be removed easily. Yet the press-fit lid is problematic, requiring much force to remove.

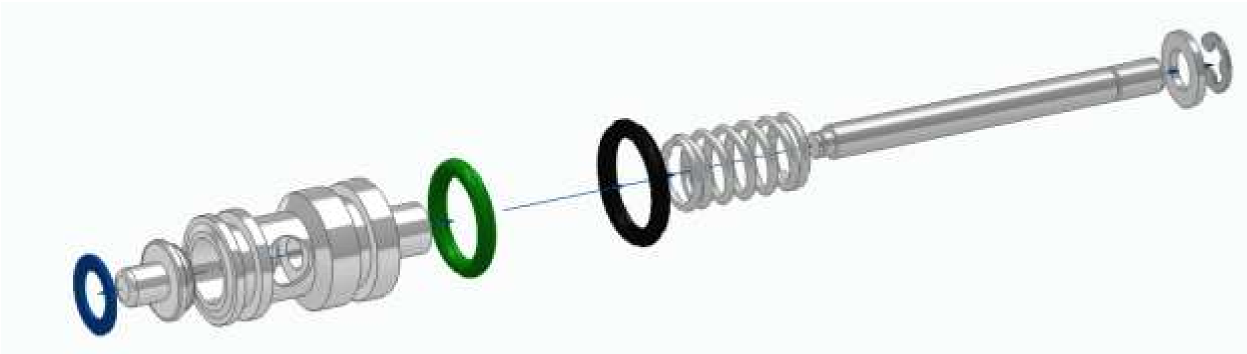


Figure 26 Gas knob control valve disassembly

4.2.4 Data Analysis and Results

DeSE Analysis

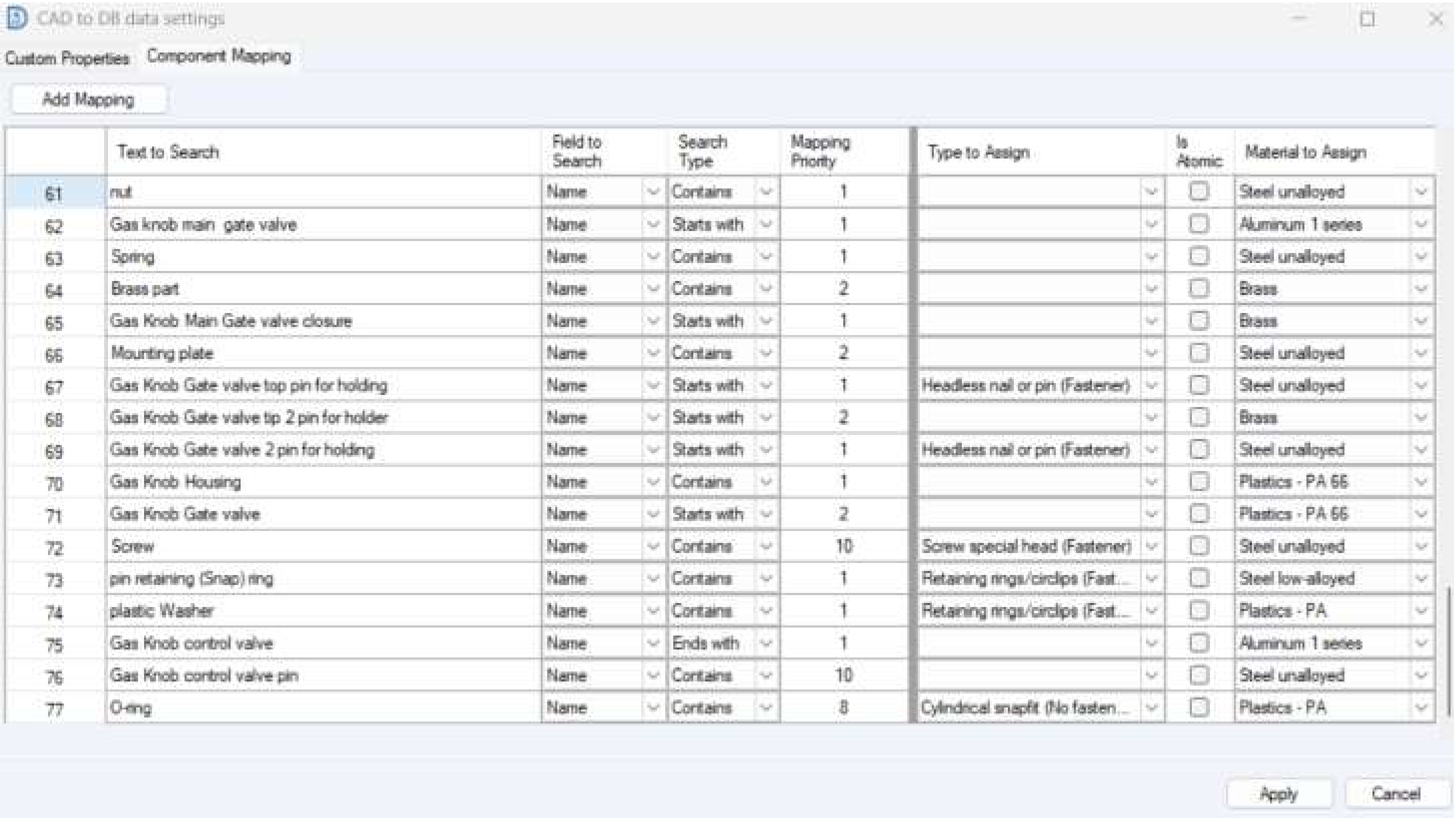
Here the study follow the same procedure that it follows in 4.1.4 section of the analysis used for gear box design

- **Importing into DeSE:** Importing the Gas knob model from Solid Edge into DeSE software.
- **Component structure:**

Table 27 Component Structure for the gas knob assembly

Component	Material	Mass [kg]	Obstruction [mm]	Is Atomic	Component Type
Gas knob Gate valve.asm	Assembly	0.19	105.09x57.85x57.83mm	No	
Gas knob switch.asm	Assembly	5.51E-03	42.30x10.04x23.51mm	No	
Gas Knob Gate valve Mounting plate screw M2.5x0.35.par (3 occurrences)	Steel unalloyed	4.28E-04	5.18x5.18x10.42mm		Screw standard head (Fastener)
Gas knob Gate and control valve top closure plate (TO BE).asm	Assembly	0.02	38.00x27.62x29.71mm	No	
Gas knob Top Housing (TO BE).asm	Assembly	0.04	72.36x72.77x163.83mm	No	

Manual mapping was performed for components not automatically identified by the software. This involved assigning material type, component type, and atomicity properties. A significant portion of the components were classified as non-atomic and are represented as sub-assemblies within the Component Structure tab.



	Text to Search	Field to Search	Search Type	Mapping Priority	Type to Assign	Is Atomic	Material to Assign
61	nut	Name	Contains	1			Steel unalloyed
62	Gas knob main gate valve	Name	Starts with	1			Aluminum 1 series
63	Spring	Name	Contains	1			Steel unalloyed
64	Brass part	Name	Contains	2			Brass
65	Gas Knob Main Gate valve closure	Name	Starts with	1			Brass
66	Mounting plate	Name	Contains	2			Steel unalloyed
67	Gas Knob Gate valve top pin for holding	Name	Starts with	1	Headless nail or pin (Fastener)		Steel unalloyed
68	Gas Knob Gate valve tip 2 pin for holder	Name	Starts with	2			Brass
69	Gas Knob Gate valve 2 pin for holding	Name	Starts with	1	Headless nail or pin (Fastener)		Steel unalloyed
70	Gas Knob Housing	Name	Contains	1			Plastics - PA 66
71	Gas Knob Gate valve	Name	Starts with	2			Plastics - PA 66
72	Screw	Name	Contains	10	Screw special head (Fastener)		Steel unalloyed
73	pin retaining (Snap) ring	Name	Contains	1	Retaining rings/circlips (Fast...		Steel low-alloyed
74	plastic Washer	Name	Contains	1	Retaining rings/circlips (Fast...		Plastics - PA
75	Gas Knob control valve	Name	Ends with	1			Aluminum 1 series
76	Gas Knob control valve pin	Name	Contains	10			Steel unalloyed
77	O-ring	Name	Contains	8	Cylindrical snapfit (No fasten...		Plastics - PA

Figure 27 Component mapping for the gas knob assembly

- **Environmental Impact Analysis**

Contrary to the gearbox, the gas knob is very different in material composition. From brass to aluminum, plastic, and even rubber O-rings, a number of materials have been used in its construction. This multi-material design, while serving specific functional requirements, contrasts sharply with the gearbox's predominantly metallic construction.

Table 28 Gas Knob Assembly Lifecycle Climate Change Impact for Incineration Scenario

Inputs	Value
Graph Type	Bar Chart
Country	Italy
EoL Strategy	Incineration
Voltage Type	Medium
Power Average [kW]	0
Use Rate [h/year]	365
Useful Lifetime [years]	10
Preventive Environmental Impact	
Lifecycle Impact	2.30
Results	
Material Phase	2.18
Use Phase	0.00
EoL Phase	0.12

Table 29 Gas knob Assembly Environmental Impact Analysis

Material Sub Category	Mass [Kg]	Material Phase [Kg CO2 eq]	EoL Phase [Kg CO2 eq]	Material Sub Category Total[Kg CO2 eq]
Plastics - Sintethic rubber	3.96e-4	1.13e-3	1.25e-3	2.38e-3
Aluminum 1 series	0.11	1.49	0.02	1.52
Steel unalloyed	0.07	0.15	3.85e-3	0.16
Plastics - PA	0.04	0.32	0.09	0.41
Brass	0.03	0.22	1.66e-3	0.22
Total	0.25	2.18	0.12	2.30

The environmental impact analysis of the gas knob shows that its lifecycle impact is dominated by the materials used in its construction. The total lifecycle impact is 2.30 kg CO2 eq, with the vast majority (2.18 kg CO2 eq) attributed to the material phase, encompassing extraction, processing, and manufacturing. The use phase contributes negligibly (0.00 kg CO2 eq), as the gas knob is human-powered. It's assumed to be incinerated, thus this end-of-life phase contributes only a fraction, 0.12 kg CO2 eq. The major materials contributing to the overall impact include aluminum 1 series, steel unalloyed, brass, and plastics like synthetic rubber and PA. This will highlight how important material selection can be in trying to reduce the environmental impact of the gas knob. This could maybe provide the chance to use either recycled or alternative options that have lower impacts.

- **Recyclability Index**

The Recyclability Index tab provides a detailed analysis of the gas knob's recyclability potential. The overall recyclability index (Rcyc) is 0.84, indicating a strong potential for material recovery. The Delta value of 105.84, also suggests high recyclability. All materials are classified as recyclable.

Table 30 Gas Knob Assembly Recyclability Index Analysis for Incineration Scenario

Field	Value
Indicator	Climate change [kg CO2 eq]
EoL Strategy	Incineration
Recyclability Index Results	
RBRn	0.89
Rcyc	0.84
Delta (%)	105.84

Table 31 Gas Knob Assembly Recyclability Index Analysis Results

Material Sub Category	Recyclable?	Mass [kg]	Recyclable Mass [g]	Mass [%]	Dn [kg CO2 eq/kg]	Vn [kg CO2 eq/kg]	Rn [kg CO2 eq/kg]	RCR [kg CO2 eq]	Mn [kg CO2 eq]
Plastics - Sintethic rubber	Yes	3.96e-4	3.96e-4	0.16	3.16	2.84	-1.81	1.59e-4	1.13e-3
Aluminum 1 series	**Yes**	**0.11**	**0.11**	**43.42**	**0.22**	**13.71**	**-19.93**	**0.09**	**1.49**
Steel unalloyed	Yes	0.07	0.07	29.04	0.05	2.12	-1.95	0.06	0.15
Plastics - PA	**Yes**	**0.04**	**0.04**	**14.83**	**2.38**	**8.63**	**-1.81**	**0.03**	**0.32**
Brass	Yes	0.03	0.03	12.55	0.05	6.88	-1.95	0.03	0.22
Total	**Yes**	**0.25**	**0.25**	**100**	**5.86**	**34.18**	**-27.46**	**0.21**	**2.18**

Aluminum constitutes the largest portion of the gas knob's mass (43.42%), followed by steel unalloyed (29.04%), then plastics PA (14.83%), and finally brass and synthetic rubber, each comprising smaller percentages. The accompanying pie chart visually represents these mass percentages. While all materials are recyclable, the varying mass contributions suggest that focusing on the recyclability of aluminum and steel would likely yield the greatest overall impact in enhancing the gas knob's end-of-life recyclability.

- **Disposal Collection**

Table 32 Gas Knob Design Disposal Collection Analysis

Sr. No.	Category	Mass (%)	Assembly (%)
1	Aluminum	0.11	43.42
2	Steel	0.07	29.04
3	Plastics	0.04	14.99
4	Copper and Brass	0.03	12.55

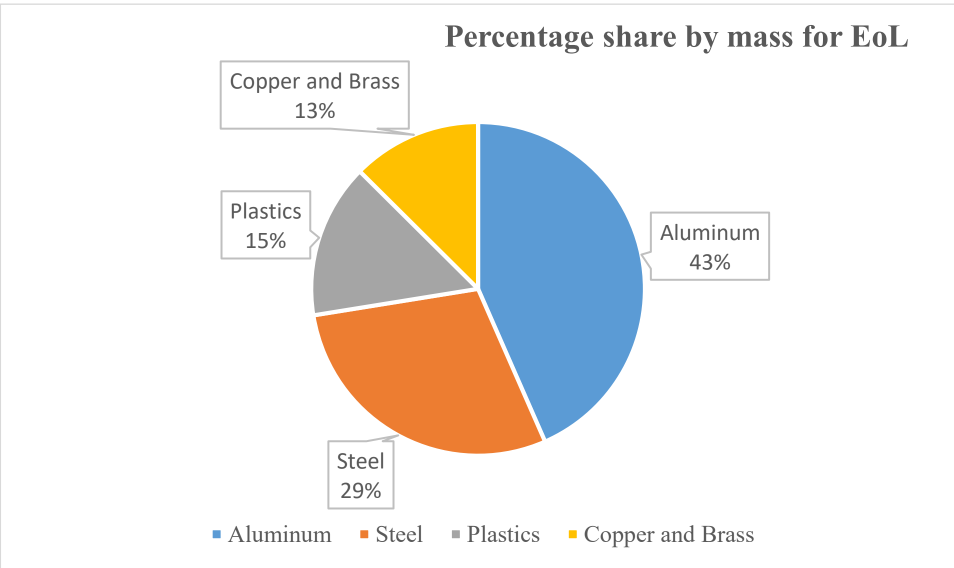


Figure 28 Gas Knob Design Disposal Collection Analysis

The Disposal Collection tab shows the materials' composition and recyclability of the Gas Knob Main Assembly. The pie chart that shows proportionate distribution of key materials, such as 43.42% Aluminum, 29.04% Steel, and 14.99% Plastics, and minor components such as Galvanized Steel, ABS Plastic, PVC, Bronze, and Brass. The table below the pie chart lists individual parts and its respective composition and weight, such as items including the Gas Knob Control Valve and the Main Gate Valve (0.10 kg), apart from a range of screws, washers, and springs. All this information comes in useful in assessing disposal-related strategies, recyclability, and effectiveness of segregation for proper disposal planning.

- **Liaisons View**

The Liaisons View tab provides a breakdown of component connections in the Gas Knob Assembly, detailing fasteners, liaison types, and recognition status. It lists various subassemblies and parts, specifying the number of components, fasteners used (e.g., screws, snap fits, interference fits), and their quantities.

Table 33 Gas knob liaisons view

Components	Number of Components	Fasteners	Number of Fasteners	Liaison Type	Auto Recognized
Gas knob Gate valve.asm/Gas knob main gate valve.par:1 + Gas knob Gate valve.asm/Gas Knob Gate valve Internal Compression spring 8.5D.par:1 + Gas knob Gate valve.asm/Gas Knob Gate valve Internal Compression spring 0.75D.par:1	3		0	Weak fit interference	No
Gas knob Gate valve.asm/Gas knob main gate valve.par:1 + Gas knob Gate valve.asm/Gas Knob Main Gate valve closure.par:1	2		0	Weak fit interference	No
Gas knob Gate valve.asm/Gas knob main gate valve.par:1 + Gas knob Gate valve.asm/Gas Knob Gate valve Brass part .par:1	2		0	Strong fit interference	No
Gas knob Gate valve.asm/Gas Knob Main Gate valve closure.par:1 + Gas knob Gate valve.asm/Gas Knob Gate valve closure seal (O-ring red).par:1	2		0	Cylindrical snapfit	No
Gas knob Top Housing .asm/Gas Knob Housing.par:1 + Gas knob Top Housing .asm/Gas Knob Gate valve .par:1	2		0	Cylindrical snapfit	No
Gas knob Top Housing .asm/Gas Knob Gate valve .par:1 + Gas knob Top Housing .asm/Gas Knob Gate valve tip 2 pin for holder .par:1	2	Gas knob Top Housing .asm/Gas Knob Gate valve top pin for holding (no round edge) .par:1 + Gas knob Top Housing .asm/Gas Knob Gate valve 2 pin for holding .par:1	2	Headless nail or pin	No
Gas knob Gate and control valve top closure plate.asm/Gas Knob Gate valve Mounting plate top.par:1 + Gas knob Gate and control valve top closure plate.asm/Gas Knob Gate valve Mounting plate cup for closure.par:1	2		0	Strong fit interference	No

Gas knob Gate valve.asm/Gas Knob Gate valve Compression spring .par:1 + Gas knob Gate valve.asm/Gas Knob Gate valve Mounting plate.par:1 + Gas knob Gate and control valve top closure plate.asm/Gas Knob Gate valve Mounting plate top.par:1	3		0	Cylindrical snapfit	No
Gas knob Gate valve.asm/Gas knob Control valve.asm/Gas Knob control valve (O-ring black).par:1 + Gas knob Gate valve.asm/Gas knob Control valve.asm/Gas Knob control valve .par:1 + Gas knob Gate valve.asm/Gas knob Control valve.asm/Gas Knob control valve (O-ring green).par:1	3		0	Cylindrical snapfit	No
Gas knob Gate valve.asm/Gas knob Control valve.asm/Gas Knob control valve pin.par:1 + Gas knob Gate valve.asm/Gas knob Control valve.asm/Gas Knob control valve pin cup.par:1	2	Gas knob Gate valve.asm/Gas knob Control valve.asm/Gas Knob control valve pin plastic Washer.par:1	1	Retaining rings/circlips	No
Gas knob Gate valve.asm/Gas knob Control valve.asm/Gas Knob control valve pin.par:1 + Gas knob Gate valve.asm/Gas knob Control valve.asm/Gas Knob control valve pin compression spring .par:1 + Gas knob Gate valve.asm/Gas knob Control valve.asm/Gas Knob control valve .par:1 + Gas knob Gate valve.asm/Gas knob Control valve.asm/Gas Knob control valve pin retaining (Snap) ring.par:1 + Gas knob Gate valve.asm/Gas knob Control valve.asm/Gas Knob control valve pin Washer.par:1	5		0	Strong fit interference	No
Gas knob Gate valve.asm/Gas knob blue seal for main gate valve.par:1 + Gas knob Gate valve.asm/Gas knob main gate valve.par:1	2		0	Weak fit interference	No
Gas knob Gate valve.asm/Gas Knob Main Gate valve closure.par:1	1	Gas knob Gate valve.asm/Gas Knob Gate valve screw (brass).par:1	1	Screw standard head	No
Gas knob Top Housing .asm/Gas Knob Housing.par:1 + Gas knob Gate valve.asm/Gas Knob Gate valve Mounting plate.par:1	2	Gas Knob Gate valve Mounting plate screw M2.5x0.35.par:1 + Gas Knob Gate valve Mounting plate screw M2.5x0.35.par:2 + Gas Knob Gate valve Mounting plate screw M2.5x0.35.par:3	3	Screw standard head	No
Gas knob Gate and control valve top closure plate.asm/Gas Knob Gate valve Mounting plate top.par:1 + Gas knob Gate and control valve top closure plate.asm/Gas Knob Gate valve Mounting plate cup for closure.par:1	2	Gas knob Gate and control valve top closure plate.asm/Gas knob Screw pin for main gate valve.par:1 + Gas knob Gate and control valve top closure plate.asm/Gas Knob Gate valve Mounting plate top nut for pin screw .par:2	2	Screw standard head	No
Gas knob Gate and control valve top closure plate.asm:1 + Gas knob Gate valve.asm/Gas Knob Gate valve Mounting plate.par:1 + Gas knob Gate valve.asm/Gas knob main gate valve.par:1	3	Gas knob Gate valve.asm/Gas Knob Gate valve Mounting plate screw M2.5x0.35.par:3 + Gas knob Gate valve.asm/Gas Knob Gate valve Mounting plate screw M2.5x0.35.par:4	2	Screw standard head	No
Gas knob Gate valve.asm/Gas Knob Gate valve Mounting plate.par:1 + Gas knob Gate valve.asm/Gas knob main gate valve.par:1	2	Gas knob Gate valve.asm/Gas Knob Gate valve Mounting plate screw M2.5x0.35.par:1	1	Screw standard head	No

- **Disassembly Index**

Table 34 Gas knob Assembly *Icom* Results

Disassembly Index	Value
Total	1.11
Min	0.21
Max	0.39
Mean	0.28

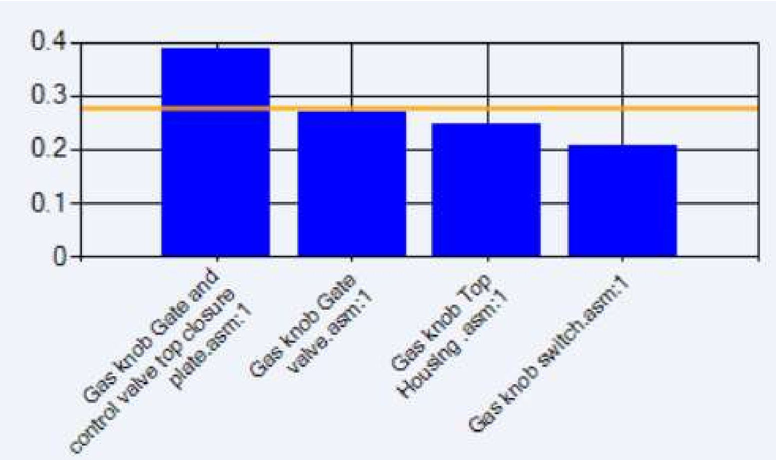


Figure 29 Gas Knob Disassembly Index Calculation and Results for Sub-assemblies

Table 35 Gas knob Disassembly Index analysis results for Sub-assemblies

Component	Description	*Ch*	*Cr*	*Icom*
Gas knob Gate valve.asm:1		0.54	0.00	0.27
Gas knob Top Housing .asm:1		0.49	0.00	0.25
Gas knob switch.asm:1		0.41	0.00	0.21
Gas knob Gate and control valve top closure plate.asm:1		0.54	0.24	0.39

The analysis of the Disassembly Index yields a quantitative evaluation of disassembly ease for individual parts in the Gas Knob Assembly. The overall disassembly complexity index is measured at **1.11**, with individual part values between **0.21 and 0.39**. On calculation of mean disassembly index, a value of **0.28** is determined, representing a general ease in disassembly. The bar chart in figure 33 shows a demonstration of individual part contribution to overall index, with values of **0.39** for both Gas Knob Gate and Control Valve Top Closure Plate, **0.27** for Gas Knob Gate Valve, **0.25** for Top Housing, and **0.21** for Switch. Index values represent ease in accessing and taking out individual parts in disassembly, with increased values representing increased difficulty in disassembly processes.

The contributing factors to the index (*Ch, Cr, and Icom*) reveal additional information about parts' behavior in disassembly processes. Handling complexity (*Ch*) values reveal uniformity in values for all parts, representing an equivalent level of difficulty in physical manipulation of parts. Recycling complexity (*Cr*) for individual parts is evaluated at **0.24** for both Gas Knob Gate and Control Valve Top Closure Plate, representing additional factors with regard to materials, structures, and respective factors for recyclability; in contrast, all other parts have a value of 0 for *Cr*, representing relatively easier removal of components. Overall complexity (*Icom*) values follow similar disassembly index, confirming both Gas Knob Gate and Control Valve Top Closure Plate as most complex parts in disassembly.

- **Disassembly Rules**

During analysis, a 0.75 level of threshold was used for this analysis to achieve a balance between detailed insight and analytical manageability. Choosing a high value for a threshold, for instance, 1.0, can mean ignoring parts with high disassembly complexity, and therefore, key factors for improvement could go unexploited. On the other hand, choosing a low value for a threshold, for instance, 0.5, can mean an overabundance of parts with little disassembly difficulty, including parts with no disassembly complexity, and therefore, prioritization of genuinely relevant factors could become cumbersome.

As seen, at a 1.0 level of threshold, no any-rule violations could be detected, and therefore, all parts could be considered for disassembly in a manner not generating warnings and redesign recommendations. With a 0.75 value for a threshold, one can practically choose parts with high disassembly complexity and at the same time refrain from an information overload, and therefore, enable a feasible distribution of resources towards effective redesign actions towards enhancing DfD and DfR.

Table 36 Gas Knobs Disassembly Rules

Rule Result	Disassembly Rule	Liaison Components	Liaison Fasteners	Liaison Type
OK	Gas knob Gate valve.asm is not critical within the chosen threshold			
OK	Gas knob Top Housing .asm is not critical within the chosen threshold			
OK	Gas knob switch.asm is not critical within the chosen threshold			
OK	Gas Knob Gate valve Mounting plate screw M2.5x0.35.par is not critical within the chosen threshold			
OK	Gas Knob Gate valve Mounting plate screw M2.5x0.35.par is not critical within the chosen threshold			
OK	Gas Knob Gate valve Mounting plate screw M2.5x0.35.par is not critical within the chosen threshold			
Warning	Gas knob Gate and control valve top closure plate.asm has a critical size rating of 0.75			
Warning	Gas knob Gate and control valve top closure plate.asm has a critical thickness rating of 0.86			
OK	Gas knob Gate and control valve top closure plate.asm's removal is not critical within the chosen threshold			

Table 37 Gas Knobs Disassembly Rules

Rule Result	Compatibility Rule
Warning	Gas knob Gate valve.asm is not compatible and Gas knob main gate valve.par:1's Icom is critical within the chosen threshold
Warning	Gas knob Gate valve.asm is not compatible and Gas Knob Gate valve Mounting plate.par:1's Icom is critical within the chosen threshold
Warning	Gas knob Top Housing .asm:1 is not compatible but its disassemblability is guaranteed
Warning	Gas knob switch.asm:1 is not compatible but its disassemblability is guaranteed
OK	Gas knob Gate and control valve top closure plate.asm:1 is compatible

The disassembly rule results show that most parts are within the tolerance values (0.75 thresholds); two significant warnings, however, have been documented regarding "Gas knob Gate and control valve top closure plate.asm," whose critical dimensions stand at 0.75 mm and 0.86 mm, respectively, in terms of thickness. Compatibility analysis reveals some warnings, most prominently with "Gas knob Gate valve.asm" and its mounting plate, and a high level of incompatibility between them. On a contrasting note, both "Gas knob Top Housing.asm" and "Gas knob switch.asm" have been deemed incompatible, yet both allow for disassembly operations to be conducted. "Gas knob Gate and control valve top closure plate" alone show full compatibility.

4.2.5 REDESIGN

4.2.5.1 Redesign of the Gas Knob Gate and Control Valve Top Closure

The original assembly of the Gas Knob Gate and Control Valve Top Closure included four critical parts: the Gas Knob Gate Valve Mounting Plate Top, the Gas Knob Screw Pin for the Main Gate Valve, the Gas Knob Gate Valve Mounting Plate Cup for the Closure, and the Gas Knob Gate Valve Mounting Plate Top Nut for the Pin Screw. In this assembly, a nut was firmly attached to a circular(ring) plate cup, acting as the base unit of the subassembly. The circular plate cup was then joined with the base rectangular plate via a hinge mechanism developed through bending of four corners of the plate.

In addition, the Gas Knob Gate Valve Mounting Plate Top Nut, which was linked with the Pin Screw Head, consisted of a slotted configuration and communicated with the gate valve guide positioned in the upper housing. It was also attached with the main gate valve opener and closer through a brass pin, secured with two additional pins. In this arrangement, effective communication with the brass pin and mounting onto a plastic gate valve, through a cam mechanism, helped in opening and closing of the gate valve.

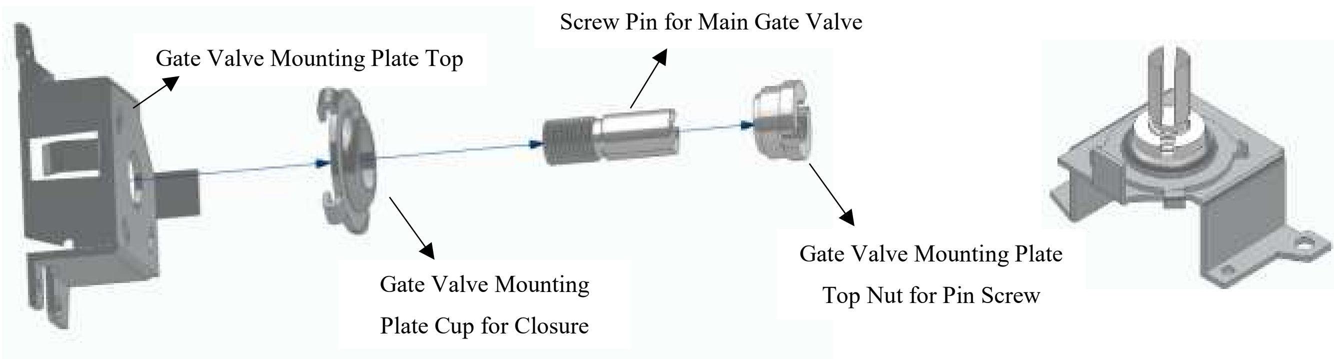


Figure 30 Gas Knob Gate and Control Valve Top Closure

The redesigned Gas Knob Gate and Control Valve Top Closure integrates and simplifies the sub-assembly by merging specific components and optimizing connections. The modifications include the integration of the Gas Knob Gate Valve Mounting Plate Top and Gas Knob Screw Pin for Main Gate Valve into a single component, eliminating unnecessary fasteners and simplifying the assembly process. Additionally, the number of brass pins used to assemble the control valve has been reduced from two to one. This single brass pin serves a dual purpose: regulating the flow of gas and securing the pin screw head. The brass pin also functions as a socket to receive the pin screw head, enhancing structural integrity and minimizing assembly complexity.

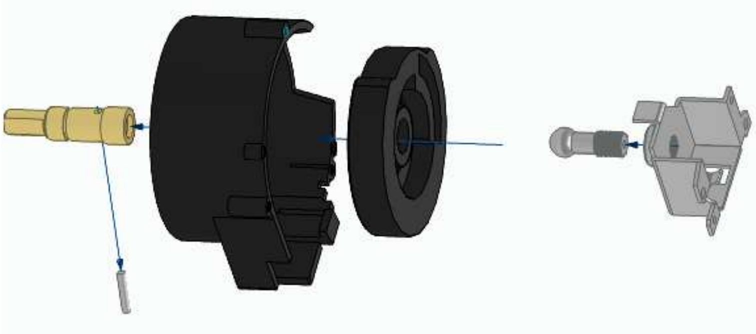


Figure 31 Redesigned Gate and Control Valve and its mounting Top Closure sub-assembly

4.2.5.2 Redesign Data Analysis

The redesigned Gas Knob Gate and Control Valve Top Closure exhibits improved disassemblability with a total disassembly index of 1.10 and a mean value of 0.27. The critical disassemblability values for individual components include the Gas Knob Gate Valve (0.27), Gas Knob Switch (0.28), Gas Knob Gate and Control Valve Top Closure Plate (0.29), and Gas Knob Top Housing (0.25). The complexity index (Icom) values indicate a balanced distribution, with the highest being 0.29 for the Gas Knob Gate and Control Valve Top Closure Plate. The redesign achieves efficient assembly and improved disassembly characteristics, optimizing both structure and ease of maintenance.

Table 38 Redesign Gas Knob Assembly Icom Results

Disassembly Index	Value
Total	1.10
Min	0.25
Max	0.29
Mean	0.27

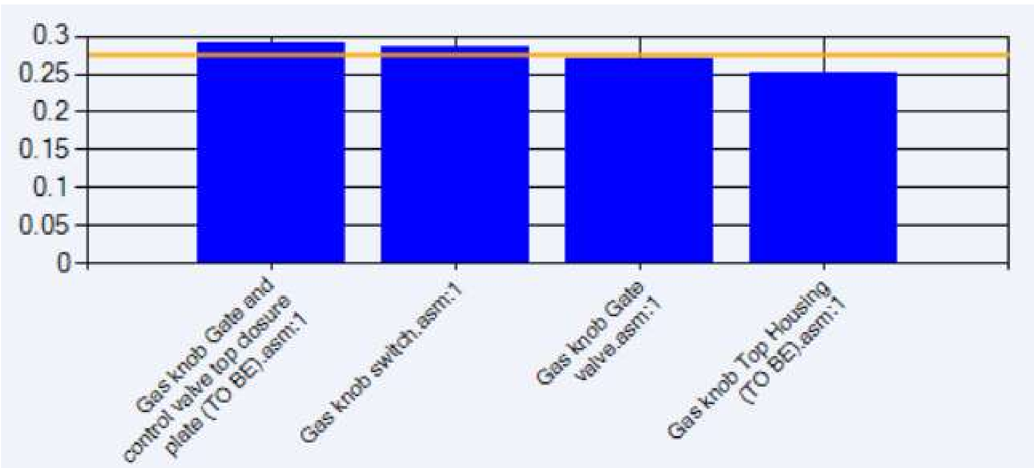


Figure 32 Redesign Gas Knob *Icom* Calculation and Results for Sub-assemblies

The redesign has succeeded in decreasing the complexity index (*Icom*) by 0.01 and removing critical disassembly issues, somehow enhancing the disassembling process. By removing the one pin, disassembly is facilitated, which is advantageous to both maintenance and end-of-life treatment.

Table 39 Redesign Gas knob Disassembly Index analysis results for Sub-assemblies

Component	Ch	Cr	Icom
Gas knob Gate valve.asm:1	0.54	0.00	0.27
Gas knob switch.asm:1	0.41	0.16	0.28
Gas knob Gate and control valve top closure plate (TO BE).asm:1	0.36	0.22	0.29
Gas knob Top Housing (TO BE).asm:1	0.50	0.00	0.25

In addition, the redesigned top plate closure, now designed as a single piece rather than three pieces, leads to enhanced manufacturability by saving scrap waste and material. The brass pin and screw ball and socket connection optimization makes the entire structure stronger and more efficient in its design.

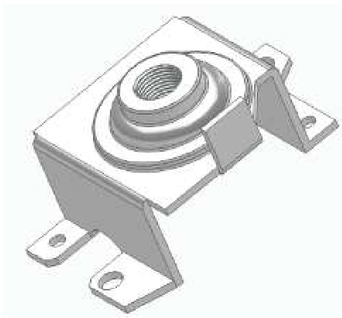


Figure 33 redesigned top plate closure

Table 40 Redesigned Gas knob Disassembly rules for Sub-assemblies

Rule Result	Disassembly Rule	Liaison Components	Liaison Fasteners	Liaison Type
OK	Gas knob Gate valve.asm is not critical within the chosen threshold			
OK	Gas knob switch.asm is not critical within the chosen threshold			
OK	Gas Knob Gate valve Mounting plate screw M2.5x0.35.par is not critical within the chosen threshold			
OK	Gas Knob Gate valve Mounting plate screw M2.5x0.35.par is not critical within the chosen threshold			
OK	Gas Knob Gate valve Mounting plate screw M2.5x0.35.par is not critical within the chosen threshold			
OK	Gas knob Gate and control valve top closure plate (TO BE).asm is not critical within the chosen threshold			
OK	Gas knob Top Housing (TO BE).asm is not critical within the chosen threshold			

Table 41 Redesigned Gas knob compatibility rules for Sub-assemblies

Rule Result	Compatibility Rule
Warning	Gas knob Gate valve.asm is not compatible and Gas knob main gate valve.par:1's Icom is critical within the chosen threshold
Warning	Gas knob Gate valve.asm is not compatible and Gas Knob Gate valve Mounting plate.par:1's Icom is critical within the chosen threshold
Warning	Gas knob switch.asm:1 is not compatible but its disassemblability is guaranteed
OK	Gas knob Gate and control valve top closure plate (TO BE).asm:1 is compatible
Warning	Gas knob Top Housing (TO BE).asm:1 is not compatible but its disassemblability is guaranteed

Also, the disassembly rules show that all the parts are Green within the threshold of 0.75 that is acceptable, ensuring that the re-designed assembly has no critical problems. The compatibility analysis ensures that parts with critical functions fulfill requirements critical to their functionality while ensuring disassembling where needed. The Gas Knob Gate and Control Valve Top Closure assembly is 100% compatible, lending to the validation of the success of the redesign. The outcome accordingly reinforces strong support for enhanced manufacturability, easier and simpler maintenance being met by the ability of the new design to embrace the overriding principles of sustainable and efficient engineering.

PART FIVE- DISCUSSION AND FINDINGS

5. Discussion

The discussion section provides a comprehensive evaluation of the findings from the disassembly complexity analysis conducted on two case studies: a gearbox for a speed reducer and a gas knob. Using a DeSE software, the study systematically examined the disassembly complexity, environmental impact, recyclability, and potential redesign improvements for both products. The primary objective was to identify areas of high disassembly complexity and propose design modifications to enhance disassembly for maintenance, recycling, and sustainability. The results obtained through DeSE software were critically analyzed to understand the performance limitations of the original designs and the effectiveness of the proposed improvements.

5.1 Main Findings

The study shows significant differences in the disassembly complexity of the gearbox and the gas knob. The gearbox was found to have a moderate-to-high disassembly complexity, with a Total Disassembly Index of 14.60, indicating that certain components required substantial effort and specialized tools for removal. The most challenging components included the Housing Closure Hexagonal with Ribs (*Icom*: 1.9, *C'r*: 3.16) due to a high number of fasteners, the Main Gearbox Housing (*Icom*: 1.18, *C'r*: 1.57) because of structural complexity, and the Shaft components (*Icom*: 1.18, *C'r*: 1.85) which required a hydraulic press for disassembly due to strong interference fits. In contrast, smaller bearings, seals, and fasteners were relatively easy to remove. The key challenges identified included excessive use of fasteners, interference fits, and limited accessibility, all of which contributed to higher maintenance complexity and longer disassembly times.

On the other hand, the gas knob exhibited a lower overall disassembly complexity, with a Total Disassembly Index of 1.11, indicating greater ease of maintenance and part removal. The majority of components were easy to disassemble, except for the Gas Knob Gate and Control Valve Top Closure Plate (Icom: 0.39), this is when it is compared to other components, which exhibited structural interference fit issues. Fasteners such as screws and snap-fits contributed minimal complexity to the disassembly process. Unlike the gearbox, the gas knob was better optimized for maintenance, with no critical disassembly issues identified at the threshold level of 1.0.

The environmental impact analysis further highlighted critical differences between the two products. The gearbox exhibited a significantly higher environmental footprint, primarily due to its high energy consumption during the use phase. The total lifecycle greenhouse gas (GHG) emissions for the gearbox were 90,793.20 kg CO_2 eq, with the use phase contributing 99.96% (90,760.18 kg CO_2 eq), highlighting the need for improved energy efficiency. The material phase contributed only 0.04% (32.13 kg CO_2 eq), primarily from low-alloy steel and cast iron, while the end-of-life impact was negligible (0.89 kg CO_2 eq) due to high recyclability.

In contrast, the gas knob had a significantly lower total environmental impact (2.30 kg CO_2 eq), with the material phase accounting for 94.8% (2.18 kg CO_2 eq) due to the use of brass, aluminum, and plastic components. The use phase had no energy consumption (0.00 kg CO_2 eq), while the end-of-life impact (0.12 kg CO_2 eq) was minimal due to plastic incineration. These results suggest that while the gearbox's operational efficiency is a major concern, the gas knob's environmental impact is more influenced by material selection.

The recyclability analysis demonstrated that both products have strong material recovery potential. The gearbox exhibited an Overall Recyclability Index (Rcyc) of 0.85, a Recyclability Benefit Ratio (RBRn) of 0.84, and a Recyclability Gap (Delta) of 99.09%, indicating excellent recyclability. The major materials contributing to recyclability included low-alloy steel (61.99%) and cast iron (27.45%), both of which are highly recyclable. The gas knob had a slightly lower Overall Recyclability Index (0.84), with aluminum (43.42%), steel (29.04%), and plastics (14.83%) forming its primary composition. While plastics and synthetic rubber components reduced recyclability, the overall potential for material recovery remained strong.

To address the identified challenges, significant redesign improvements were proposed. For the gearbox, the housing redesign focused on reducing the number of fasteners by 50% by optimizing the connection between the secondary housing and the primary gearbox housing and introducing a snap-fit mechanism, which successfully lowered the Disassembly Index from 14.60 to 9.88. The shaft and gear redesign replaced interference fits with spline connections, reducing the need for a hydraulic press during disassembly and making maintenance easier. These modifications not only improved accessibility and ease of disassembly but also maintained high recyclability (Rcyc: 0.85) while enhancing energy efficiency.

The gas knob required less extensive redesign due to its already optimized disassembly structure. The primary modification was made to the Gas Knob Gate and Control Valve Top Closure, where the number of brass pins was reduced from two to one, and fastener complexity was minimized. This resulted in a slight reduction in the Disassembly Index from 1.11 to 1.10, ensuring improved ease of maintenance and assembly efficiency while maintaining high recyclability (Rcyc: 0.84).

In conclusion, the findings of this study emphasize the importance of DfD in product optimization. The gearbox redesign significantly reduced disassembly complexity, improved recyclability, and enhanced energy efficiency, while the gas knob's structural design required only minimal modifications. By addressing key challenges related to fasteners, fit interference, and accessibility, the study successfully demonstrated how engineering design improvements can lead to more sustainable, efficient, and maintenance-friendly products.

5.2 Comparison of Results: Before vs. After Redesign

The comparison between the original and redesigned gearbox and gas knob assembly highlights improvements in disassembly complexity, environmental impact, recyclability, and structural efficiency. The redesign focused on reducing fasteners, optimizing connections, and improving material selection to enhance ease of maintenance, sustainability, and recyclability.

The table 15 and 16 presents a comparison of key performance indicators seen during the analysis and results obtained before and after the redesign:

Table 42 Gearbox Comparison (Before vs. After Redesign)

Criteria	Before Redesign	After Redesign	Improvement Achieved
Total Disassembly Index	14.60	9.88	-32.32% (Easier disassembly)
Most Complex Component (Icom)	Housing Closure Hexagonal with Ribs (1.9)	Housing Closure Hexagonal with Ribs (1.06)	-44.2% Complexity Reduction
Average Disassembly Index (Icom)	0.66	0.55	-16.6%
Fasteners Used	10 Hexagonal Bolts and 4 Allen Bolts	5 Hex. Bolts, 4 Allen Bolts and Snap fit Mechanism	-50% in number of fasteners for connection between the secondary housing and the primary gearbox housing
Main Shaft & Gear Connection	Interference Fit (Requires Hydraulic Press)	Spline Connection (No Press Required)	< Assembly/Disassembly Effort
Overall Recyclability Index (Rcyc)	0.85	0.85	No Change (Still High Recyclability)
Total Environmental Impact (kg CO_2 eq)	90,793.20	90,760.18	-0.036%

Material Composition	Steel Low-Alloy (61.99%), Cast Iron (27.45%)	Steel Low-Alloy (62%), Cast Iron (27.4%)	Minimal Change (High recyclability retained)

Table 43 Gas Knob Comparison (Before vs. After Redesign)

Criteria	Before Redesign	After Redesign	Improvement Achieved
Total Disassembly Index	1.11	1.10	- 0.9% reduction
Most Complex Component (Icom)	Gas Knob Gate and Control Valve Top Closure (0.39)	Gas Knob Gate and Control Valve Top Closure (0.29)	- 25.64% Complexity Reduction
Average Disassembly Index (Icom)	0.28	0.27	-3.57% reduction
Fasteners Used	2 Pins, Screws	1 Brass Pin + Fewer Screws	-50% in number of fasteners for Top gate valve closure and its housing
Overall Recyclability Index (Rcyc)	0.84	0.84	-
Total Environmental Impact (kg CO_2 eq)	2.30	2.29	-0.43%
Material Composition	Aluminum (43.42%), Steel (29.04%), Plastics (14.83%)	Aluminum (43.5%), Steel (29%), Plastics (14.5%)	-

5.3 Coherence of Results and Observations

The coherence of the results obtained through DeSE software analysis and the observations made during disassembly reflects a high degree of consistency, reinforcing the reliability of the findings. This section examines the alignment between the calculated disassembly complexity, recyclability assessments, environmental impact evaluations, and hands-on observations during the analysis of the gearbox and gas knob assemblies.

5.3.1 Alignment of Disassembly Complexity with Observations

The disassembly complexity indices (*Icom*, *C'h*, and *C'r*) computed using DeSE software were largely in alignment with the physical observations made during the study.

- For the gearbox, the housing closure, shafts, and gear connections were identified as the difficult components and labor intensive to disassemble, which aligned with the observed difficulties in accessing and removing these parts.

- The strong interference fit of the shaft and gear assembly, which required a hydraulic press for removal, was confirmed as a key contributor to high disassembly complexity in the software analysis and practical observations.
- The gas knob, in contrast, was easier to disassemble, as DeSE results showed lower complexity indices, which was also evident in the manual disassembly process.

The redesign efforts successfully addressed these concerns, as reflected in both theoretical calculations and practical assessments. The design of a spline connection for the gearbox shaft and gear eliminated the need for a hydraulic press, making the disassembly process simpler and more efficient. Similarly, the reduction of fasteners and improved snap-fit mechanisms in both products led to a measurable decrease in disassembly complexity indices, confirming that the software's predictions aligned with real-world improvements.

5.3.2 Consistency in Environmental Impact Findings

The environmental impact analysis using DeSE software showed that the gearbox had a significantly higher carbon footprint than the gas knob, primarily due to its energy-intensive usage phase. This was consistent with practical expectations, as gearboxes in industrial and automotive applications operate under continuous high-power loads, leading to substantial energy consumption over time.

The use phase contributed 99.96% of the gearbox's total CO_2 emissions, a finding that accurately reflects the dominant role of energy consumption in industrial mechanical systems.

For the gas knob, the environmental impact was primarily associated with material extraction and manufacturing, as expected for a mechanical component that does not consume energy during operation. The negligible end-of-life impact confirmed the high recyclability of aluminum and steel components, which matched real-world expectations.

Despite the marginal reduction in environmental impact after redesign, both products remained within the expected sustainability performance range, reinforcing the accuracy of the software's life cycle assessment calculations.

5.3.3 Validation of Recyclability Analysis

The high recyclability indices (Rcyc: 0.85 for the gearbox and 0.84 for the gas knob) predicted by DeSE software were in agreement with material composition assessments. The majority of materials used—low-alloy steel, cast iron, aluminum, and brass—are well-known for their high recyclability, which was further validated by manual inspection.

The gearbox's high percentage of steel and cast iron made it a suitable candidate for material recovery, aligning with the software's recyclability assessment.

The gas knob contained a mix of recyclable metals and plastics, and the low percentage of synthetic rubber and plastic components confirmed that most of its materials could be efficiently recovered, consistent with DeSE's recyclability index results.

5.4 Challenges during Study

5.4.1 Challenges in Study

The study encountered a variety of challenges, predominantly in disassembling parts, searching for literature, and getting to understand materials and training in software.

A significant challenge involved disassembling parts such as shafts, gears, and bearings, and these require a hydraulic press. Because parts could not be disassembled, taking apart, and then taking a measurement, checking for some DeSE software output became challenging.

A lack of in-depth literature regarding disassembly complexity indices *(Icom, C'r, and C'h)* posed a challenge, and it became challenging to analyze because such indices lack documentation, and therefore, it is challenging to validate them. To mitigate this problem, studies concerning DfD and LCA were utilized in the study.

Generalizing materials' composition posed a challenge in general. There was no concrete information regarding steel alloys, types of plastics, and rubber types, and therefore minor inaccuracies in analysis for recyclability and for environment impact analysis, and this is because materials have variable property and factors for sustainability.

Lastly, training in software, particularly Solid edge, initially posed a challenge in terms of its format and model requirements.

In spite of all these, the study utilized alternative sources for information collection, made educated estimates regarding material property, and referenced additional studies for meaningful and reliable analysis in its output.

PART SIX – CONNCLUSION AND RECCOMENDATION

6.1 Conclusion

This study systematically evaluated the disassembly complexity, environmental impact, and recyclability of a speed reducer gearbox and a gas knob assembly, using DeSE software to quantify disassembly difficulty and identify design inefficiencies. The findings highlighted significant challenges in the gearbox's disassembly process, particularly interference fits between shafts and gears, as well as excessive use of fasteners, which contributed to high handling and removal complexity. Conversely, the gas knob assembly exhibited lower disassembly complexity.

To address these challenges, a redesign strategy was implemented, focusing on reducing fasteners, optimizing shaft and gear connections, and simplifying component integration. The gearbox redesign included replacing interference fits with spline connections and cutting fastener use by 50% by optimizing the connection between the secondary housing and the primary gearbox housing, resulting in a 32% reduction in the Total Disassembly Index, making it significantly easier to disassemble, repair, and recycle. The gas knob redesign, while less extensive, focused on reducing redundant fasteners and optimizing connections, leading to a slight improvement in disassembly efficiency.

The environmental impact analysis showed that the gearbox's primary environmental burden came from its energy-intensive use phase, which contributed 99.96% of its total CO_2 emissions. This finding emphasizes the need for efficiency improvements in operational performance to minimize its carbon footprint. In contrast, the gas knob's impact was largely attributed to material extraction and manufacturing, reinforcing the importance of sustainable material selection and improved recyclability. Both products retained high recyclability potential, with Rcyc of 0.85 for the gearbox and 0.84 for the gas knob, confirming their suitability for circular economy applications.

Some challenges were encountered during the study, including difficulty in physically disassembling the gearbox due to strong interference fits and the need for a hydraulic press, which prevented full manual disassembly. Additionally, limited literature on disassembly complexity indices (*Icom, C'r, and C'h*) made validation more challenging, requiring reliance on related studies in DfD and Life LCA. Another challenge was the generalization of material composition, as exact material specifications were unavailable, leading to minor uncertainties in recyclability and environmental assessments. The learning curve associated with Solid Edge CAD software also presented an initial barrier but was eventually overcome.

Despite these challenges, the study successfully demonstrated the effectiveness of digital disassembly analysis tools in identifying design inefficiencies and guiding redesign improvements. The findings reinforce the importance of integrating DfD and DfR principles into mechanical product development to enhance ease of maintenance, reduce environmental impact, and improve recyclability. The redesign efforts led to measurable improvements in both ease of disassembly and structural efficiency, providing a practical framework for future design enhancements.

Applying systematic disassembly analysis and redesign principles, manufacturers can create products that are easier to maintain, more environmentally friendly, and more efficient throughout their lifecycle, aligning with modern sustainability goals and circular economy principles.

6.2 Recommendation

Based on the study findings, recommendations are provided in two areas: general recommendations for improving product design and sustainability and specific recommendations for enhancing DeSE software functionality to improve efficiency and user experience.

6.2.1 General Recommendations

- Reducing the number of fasteners and interference fits can significantly improve the ease of disassembly. It is recommended that, where possible, snap-fit mechanisms or modular designs be implemented to facilitate easier maintenance and recycling
- It is recommended that, where possible, snap-fit mechanisms or modular designs be implemented to facilitate easier maintenance and recycling.
- Since the gearbox's primary environmental impact arises from its energy-intensive use phase, future designs could prioritize improving energy efficiency by reducing friction, optimizing lubrication, and using lightweight but durable materials.
- To further refine product design, CAD-integrated simulation tools can be used to analyze and optimize disassembly sequences before manufacturing, reducing inefficiencies and minimizing assembly complexity.
- The integration between CAD software, DeSE software, and Life Cycle Assessment (LCA) tools may be enhanced to streamline data exchange and reduce the need for manual data

entry. Ensuring seamless compatibility across these platforms would save time and improve accuracy.

6.3 Recommendations for DeSE Software Improvement

- The current file-saving system requires users to either save as a new file each time (leading to excessive file creation) or overwrite the existing file manually. It helps to save time if an auto-save feature applied, along with quick-save shortcuts (e.g., Ctrl + S, similar to Microsoft applications) to enhance user convenience.
- The absence of Undo (Ctrl + Z) and Redo (Ctrl + Y) functions makes corrections time-consuming. Adding these features would allow users to efficiently reverse mistakes without manually repeating steps.
- Currently, users must manually input material properties during component mapping, which is time-consuming for complex designs. Making DeSE's material library compatible with Solid Edge's material database would allow for automatic material mapping, significantly reducing manual workload.
- When a CAD file is updated, DeSE does not automatically reflect these changes, forcing users to re-import and repeat the mapping as well as liaison steps. Implementing real-time synchronization would ensure that modifications in the CAD model are immediately reflected in DeSE, especially for iterative redesign processes.
- When a file is reopened after closing, its integration with Solid Edge is lost, preventing component highlighting when selecting parts in DeSE. This issue should be addressed to ensure that CAD-linked components remain identifiable even after reopening a project.
- During liaison selection, users face difficulties in sorting components and ensuring accurate selection. A feature would introduced to allow sorting in ascending or descending order, ensuring that when users select components for liaisons, the correct components are added instead of mistakenly selecting those originally in that row.
- Occasionally, files become corrupted upon reopening without a clear reason. Recommend a better file recovery mechanism implementation, along with automatic backup options, to prevent data loss.
- While assigning liaisons, DeSE allows an unlimited number of popup windows to open simultaneously, cluttering the interface and causing confusion. A restriction would be placed to allow only one popup window at a time, with a blinking notification or message on the already opened window to guide users.

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