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HDD Disassembly Optimization for the Efficient Recovery of NdFeB Permanent Magnets

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Abstract

Permanent magnets are widely used in various sectors, including electronics, electric motors, and wind turbines. However, these magnets are produced from critical materials, making it imperative to find solutions for their reuse and recycling. This study focuses on the analysis and optimization of disassembly processes for permanent magnets from hard disk drives, aiming to enhance the profitability and efficiency of magnet recovery. By streamlining the disassembly process, the research seeks to favour either the direct reuse or the recycling of recovered magnets, contributing to sustainable practices in WEEE recycling and reducing dependency on critical raw materials.

Keywords: Hard Drive Disks; Optimal Disassembly Level; NdFeB Permanent Magnets.

1. Introduction

Rare earth elements (REEs) encompass the lanthanide series (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu), along with scandium (Sc) and yttrium (Y) [1]. Despite their name, REEs are not particularly uncommon; the majority of them have a notable presence in the Earth's crust [2]. However, natural abundance of an element does not mean ease of extraction. Indeed, these materials are typically found in non-economically viable concentration and because their bearing minerals are usually associated with Ca, Th and U, their exploitation is related to environmental issues [2].

Due to their unique magnetic, phosphorescent, and catalytic properties arising from the electron configuration in the 4f orbital [1], REEs play a vital role in numerous advanced technologies. Their demand has been steadily increasing, primarily driven by their essential function in clean energy production and the green economy. REEs are utilized in a variety of applications, including catalysts, permanent magnets, ceramics, glass, and batteries, across industries such as electronics, automotive, and renewable energy.

Since the early 1990s, China has been the primary global supplier of REEs, accounting almost for 98% of European market supply today [3]. Nevertheless, growing domestic demand in recent years has led to export restrictions, resulting in significant supply risks [4]. This decision drives the European Commission to regard REEs as one of the most critical groups of raw materials, while the U.S. Department of Energy (DOE) has specifically identified five of them (Nd, Eu, Tb, Dy, and Y) as particularly strategic [4].

The attention of the present paper is on Nd and Dy, which find their key application in NdFeB permanent magnets (PMs) production [5]. The remarkable magnetic properties of miniature and lightweight NdFeB magnets, including high remanence, coercivity, and maximum energy product, make them essential for a wide array of applications [6]. These range from small devices such as hard disk drives (HDDs) in PCs and laptops, smartphones, and music players, to large-scale industrial applications, including electric vehicles, wind turbines, refrigerators, and medical equipment.

Despite the high recycling potential, end-of-life (EoL) NdFeB magnets are significantly underutilized. This is even

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more concerning if one considers that EoL PMs contain approximately 15–30% REEs, while natural deposits have less than 5%. Today, the global recycling rate for REEs remains below 1%, hindered by technological challenges, inefficient collection systems, and insufficient economic incentives [7].

In general, an effective NdFeB recycling process must be able to:

- Selectively recovering REEs with high purity;
- Adapting to diverse compositions and concentrations;
- Minimizing environmental impact, such as energy use and waste generation.

These challenges, combined with the physical properties of NdFeB magnets— which cause them to stick to shredders, leading to agglomeration and operational downtime—along with the high variability of products, create significant obstacles in recycling processes. Typically, manual dismantling is required, but the necessities of considerable labor, expertise, and specialized tools make this approach commercially unfeasible.

Researchers emphasize that robotic sorting and dismantling are crucial for applications at an industrial scale [5]. However, significant limitations in design for disassembly continue to restrict its broader implementation. To overcome these challenges, the definition and standardization of optimal disassembly levels is a pivotal action to streamline the process.

Keeping in mind the considerations made so far, this research focuses on permanent magnets from HDDs. They are indeed becoming an increasingly significant waste stream in WEEE as the demand for data storage grows and newer solid-state drives (SSDs) progressively replace HDDs [8]. HDDs are estimated to account for 11%[4] to 18%[5] of permanent magnet usage: Google alone retires about 300.000 HDDs each month [5]. Therefore, although the amount of PMs per unit of HDD is small, they can be considered a viable solution to recover a significant quantity of permanent magnets.

While [8] suggests a disassembly sequence considering the added value of each component to prioritize the recovery of valuable materials (i.e. NdFeB magnets, PCBs, and spindle motors), [5] presents a semi-automatic system for recovery NdFeB magnets from HDDs. More recently, [9] and [10] further investigated the topic by implementing a visual intelligence scheme for HDD automated disassembly [9] and a hybrid disassembly line considering human-robot collaboration [10]. Nonetheless, the solutions proposed in the literature do not extensively account for the variability in HDD designs across different brands.

This work investigates the designs of various 3.5” HDDs sourced from a local recycling plant, identifying possible internal configurations. Three primary disassembly graphs will be presented, demonstrating that while the overall structure is consistent, variations in the connection methods of specific components significantly affect disassembly times and sequences. Based on these findings, an optimal configuration for NdFeB magnet recovery is then proposed, along with an optimized disassembly sequence for the best-case scenario.

It is worth noting that the purpose of this work is not to suggest an optimal design configuration for HDD production, as it is a commonly accepted fact that the market for HDD is shrinking. Rather, it serves as a preliminary step toward recognizing HDD designs in order to facilitate optimal disassembly sequences, thereby maximizing recycling potential.

2. Material and Methods

2.1. HDD Processing

The disassembly analysis was conducted on a sample of 44 3.5" HDDs. Among these, over one-third were from Seagate (39%), 20% from WD, 18% from Maxtor and 7% from Samsung, with the remaining units representing a mix of other brands.

During the HDD disassembly the time required to remove each component and the standard deviations were recorded, with an effort to isolate also those data related to the fasteners.

Based on these results, the corresponding precedence graphs were then reconstructed through a component-oriented approach.

2.2. Disassembly optimization software

Following the disassembly activities, an optimization software previously developed internally by the Department of Mechanical Engineering at Politecnico di Milano was employed to determine the optimal task sequence. The software generates optimization outputs based on several objective functions:

- Minimizing setup cost;
- Maximizing disassembly income;
- Achieving line balancing;
- Performing multiclass analysis.

For each configuration analyzed, it received as input the list of components, along with their mean times, standard deviations, and disassembly directions. Disassembly tools were also documented, with efforts made to associate them with the specific components they are intended to remove. Additionally, if a component’s disassembly direction differed from that of the previous component, the time required to rotate the product was recorded.

To optimize the process, the program combines the input data with the precedence constraints. These constraints are represented by an $n \times n$ binary matrix (where n represents the number of tasks), in which each cell has a value of 1 if the disassembly of the component in the i-th row requires the removal of the component in the j-th column, and 0 otherwise. Whenever a component has multiple precedence requirements, more than one "1" will be marked in the same row.

2.3. Experimental approach

Among the four proposed objective functions, the decision was made to prioritize minimizing setup costs. This choice is primarily tied to the research project context of this study: the European project HARMONY. The ultimate goal of the project is indeed the recovery of permanent magnets. As such, since the target components were already a constraint, the proposed solution was chosen to identify the fastest partial disassembly sequence.

Despite the adopted choice, it is worth noting that evaluating potential outcomes based on the maximal income disassembly approach would be of interest too. In this regard, it could be valuable to explore integrating the optimization program we developed with the economic evaluations conducted by [8], possibly also estimating the times obtained through automated disassembly [5], [9], [10].

Considering that the output of the manual HDD disassembly is not merely the magnet, rather an assembly of the magnet and a metal plate (Figure 1), qualitative results related to their separation are also presented. Specifically, both a mechanical approach and a thermal approach were tested. While the first one was designed to deform the metal plate for easier removal of the magnet, the latter aimed to achieve two objectives: the evaporation of the adhesive bonding the two components and the demagnetization of the NdFeB permanent magnet (PM).

In the final section, a qualitative analysis of the profitability of additional components identified as suitable for industrial disassembly is reported.

Figure 1: Actuator magnets and metal plates. Almost each HDD has two of them; they have the same dimensions and can be either similar to the left (small) one or the right (big) one.

3. Results and Discussion

As a result of our experimental campaign, a total of three distinct standard configurations were identified. With the exception of some minor differences (such as the use of different types of screws and slight variations in the design and shape of internal components), each of the HDDs analyzed could be placed into one of these configurations.

Table 1 provides the list of the components that have to be removed to obtain the magnets, their disassembly times, and standard deviations. Each time was calculated considering a non-destructive disassembly.

Table 1: Disassembly tasks, Mean times and standard deviations.

Task	Mean time [s]	Std. Dev. [s]
Top casing screws	61,5	19,6
Top casing	7,6	14,0
PCB screws	27,0	12,1
PCB	1,0	0,9
Rear screw covers	14,5	13,4
Upper actuator magnet (+ metal plate) screws	7,9	6,2
Upper actuator magnet (+ metal plate)	3,8	3,7
Front actuator PCB head screws	9,5	2,5
Rear actuator PCB head screws	3,8	2,0
Actuator PCB head	3,5	3,7
Latch	1,7	1,6
Ramp screw	6,7	1,8
Ramp	2,6	1,2
Rear read-write head screw	49,7	80,0
Front read-write head screw	22,8	50,4
Read-write head	1,3	0,7
Lower actuator magnet (+ metal plate) screws	10,5	5,9
Lower actuator magnet (+ metal plate)	2,6	3,9

With the exception of the latch and the ramp (along with the respective screw), the same components are present in each HDD. Also, note that when the read-write head screw or the actuator PCB head screws are positioned frontally, they are not present in the rear of the product and vice versa. The association with a specific configuration is hence determined mainly by the positioning of the components, their attachment methods, and the required directions for removal.

In general, it can be observed that the most time-consuming activity is associated with the removal of the screws on the top casing. This is attributed to the high number of screws (typically 7 or 8) and the presence of a central screw that is covered by an adhesive label, which prolongs the removal process. Conversely, the various internal configurations of hard drives result in significant variability in the activities related to the extraction of the read-write head screws.

Below are presented the results pertaining to each analysis case.

3.1. Case 1

This configuration is the most complex of the three. The complexity is due both to the greater number of components that need to be disassembled and to the changes in the removal directions.

The HDDs belonging to this category are characterized by the presence of a rear screw that secures the read-write head to the body of the product; this necessitates the removal of the PCB located at the back to access the aforementioned screw.

It should be noted that this case is the least common. In fact, less than 20% of the HDDs fall into this category, although no correlation with specific production cases has been identified. The occurrence of the respective brands is as follows:

- 3 HDDs from Seagate (Skyhawk and Barracuda 7200.11 models);
- 1 HDD from IBM (Dnes model), HP (Dpss model), Quantum (Atlas model), Samsung (Sp0812c model), and Maxtor (Atlas 10k IV).

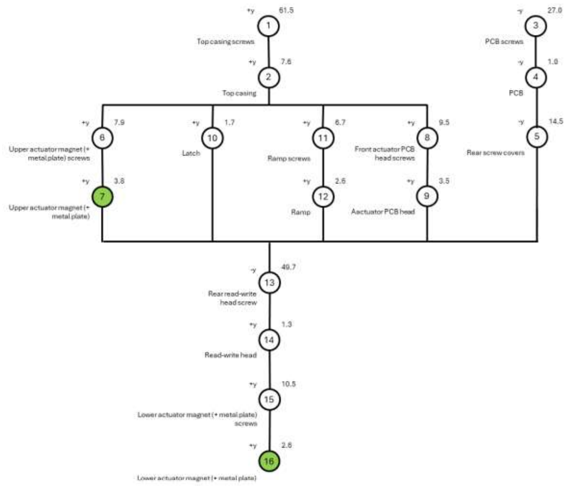

Figure 2: Case 1 - Component oriented disassembly precedence graph. The green items are the targets.

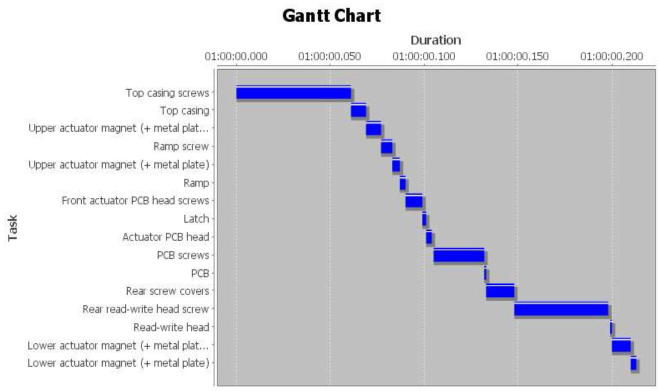

Figure 3: Case 1 - Gantt diagram representing the optimal disassembly sequence.

In this case, the disassembly time is estimated at just under 215 seconds, with a relatively high standard deviation of approximately 171 seconds due to the aforementioned reasons. Further complicating the process, it has been verified that when the read-write head screw is positioned at the rear, it becomes more difficult to access and may sometimes be stripped.

The precedence graph in the component-oriented version is shown in Figure 2. In this specific case, the Gantt chart (Figure 3) is also provided, illustrating the optimal disassembly sequence for the HDDs in Case 1.

In a very few cases, the screw securing the actuator PCB head to the HDD metal body may be located on the back, underneath the PCB. In these HDDs, that screw should be removed after the rear screw covers. This configuration results in a slightly lower total time and standard deviation as there is only a single screw (in contrast to the two present when the attachment is frontal).

3.2. Case 2

The HDDs in this second case differ significantly from those in the previous one due to a key detail: the placement of the read-write head screw. The front-facing position of this screw makes it unnecessary to disassemble the PCB and the rear components of the product, given that the primary goal is solely to recover the magnets. Furthermore, since each part in this configuration has the same extraction direction (i.e., +y), the two rotations required to remove the rear components in the previous case are eliminated.

As can be expected, both time and standard deviation decrease substantially, being estimated approximately at 142 and 115 seconds, respectively. Although the front positioning of the read-write head screw facilitates its extraction, the variability associated with its wear conditions still has a notable impact on the final output. Nonetheless, it is worth noting that this variability is mainly due to isolated cases, and in the majority of HDDs, its removal presents no complications.

The models in this category are predominantly from WD. In fact, 8 out of 9 HDDs from this brand displayed the configuration shown in Figure 4. Additionally, there are two other HDDs, one each from IBM and Hitachi.

Anticipating the details that will be elaborated in the following paragraph, it should be noted that the only feature distinguishing Case 2 from Case 3 is the presence of the latch and ramp. It can thus be stated that the addition of these components is almost exclusively associated with the WD manufacturer.

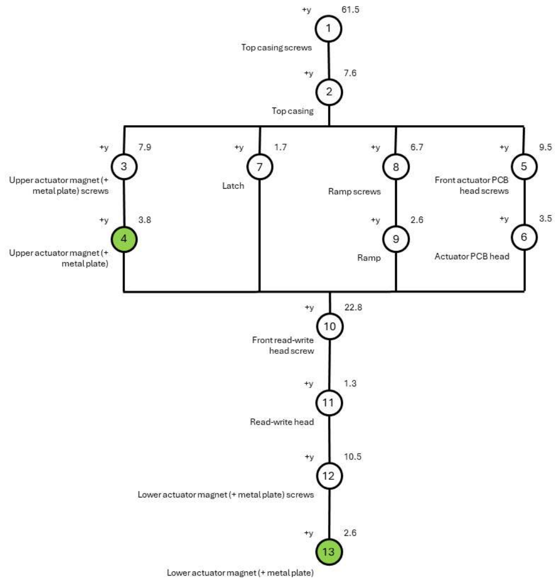

Figure 4: Case 2 - Component oriented disassembly precedence graph. The green items are the targets.

3.3. Case 3

As just mentioned, this last case is very similar to the previous one and could easily be classified as Case 2.2. The only difference lies in the absence of the latch and ramp within the HDDs. Therefore, prior removal of these components to extract the read-write head—and consequently the second magnet—is unnecessary. This design choice offers additional incremental benefits over those highlighted in the previous case. The disassembly time is the shortest of the three, with completion estimated at just over 2 minutes (approximately 130 seconds) while the standard deviation nearly unchanged from Case 2 (around 110 seconds).

Most of the examined waste falls into this category, with many models belonging to the brands Seagate, Maxtor, and Samsung. A smaller number of HDDs were associated with other brands, such as Fujitsu and IBM.

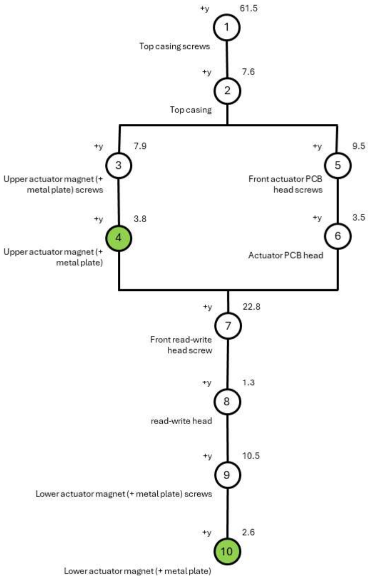

Figure 5: Case 3 - Component oriented disassembly precedence graph. The green items are the targets.

3.4. Separation of the permanent magnet from the metal plate

This final section aims to evaluate two different methods for separating permanent magnets from the metal plates to which they are bonded. This step is considered crucial before crushing the magnet for recycling: since the magnet and the metal plate have masses of the same order of magnitude, premature crushing without prior separation would significantly reduce the purity of the shredded material.

To accomplish this task, two solutions were adopted: a mechanical separation and a thermal one.

3.4.1. Mechanical separation

In the initial phase of the research project, a mechanical separation was hypothesized. This approach involves plastically deforming the metal plate to facilitate the extraction of the magnet by leveraging a screwdriver. This method was analyzed due to its simplicity and rapid execution. It is sufficient to secure the plate in a vise and apply an impulsive force to achieve the desired result.

The outcome of this method is an unsintered magnet, which may be useful for potential reuse. In this case, complications may arise when the magnet breaks or when the protective coating is partially removed. However, in a more realistic recycling application context, the necessity for demagnetization becomes critical, which suggests the need to couple the current approach with an alternative method.

3.4.2. Thermal separation

Based on the findings from the previous approach, the idea of a separation following the heating of the assembly was developed. In this case, the increase in temperature serves a dual purpose: to demagnetize the magnet (either partially or completely, with the latter option being mandatory for subsequent shredding) and to evaporate the adhesive binding the two components. This method is significantly longer than the previous one and it is also more energy-intensive. However, it effectively combines the need for separation with the requirement to obtain a demagnetized magnet that can be fed into the shredder.

Figure 6 displays the effects of temperature on the adhesive. Alongside the colour change, which indicates its complete evaporation as temperature increases, it is interesting to note the quantity of coating removed in each scenario. This quantity is notably high in cases where separation occurs at room temperature, particularly with larger magnets, and gradually decreases as the sample is exposed to higher temperatures.

Literature suggests temperatures ranging from 300 to 500 °C [7]; based on our findings, an exposure to 300 °C produces satisfactory results while effectively minimizing energy consumption.

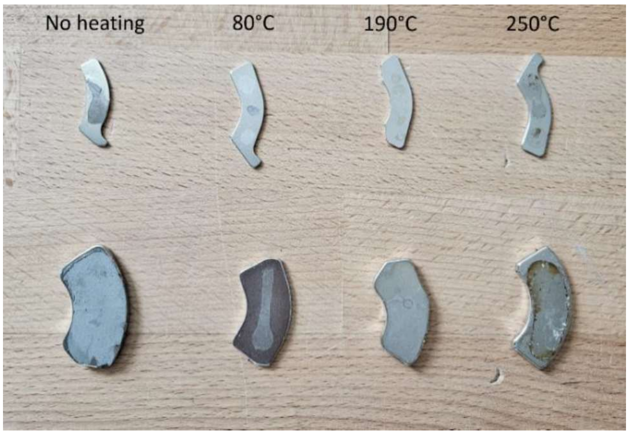

Figure 6: Effect of exposure to different temperatures on adhesives for bonding permanent magnets to metal plates.

3.5. Additional profitable parts disassembly

In addition to the actuator magnets, other components with potential profitability in terms of raw material recovery can also be identified. PCBs and spindle motors are prime examples of such parts [8].

On the one hand, PCB disassembly can be seen almost always profitable. Its estimated value alone has already been considered more than sufficient by [8] to justify complete disassembly of the HDD, including that of the spindle motor. Our findings not only support this assertion but also suggest that in disassembly processes aimed at profit maximization, PCB removal should always be performed. Due to its positioning, the PCB is quick to remove (27 seconds for the screws + 1 second for the PCB itself) and represents the activity with the highest added value.

The same cannot be said for the permanent magnets (PMs) contained within the spindle motor. These magnets not only have significantly lower mass compared to the two actuator magnets but are also difficult to access. Several components must be removed before they can be reached, resulting in a time-intensive process. Additionally, the motor is firmly integrated with the HDD structure, making complete separation from the device nearly impossible. Attempting to recover these magnets through the previously described mechanical process would likely result in significant breakage of the PMs. At the same time, preheating the entire unit to facilitate removal is impractical given the bulk of the HDD body, which would drastically reduce throughput, rendering the recovery process unjustifiably inefficient for such a small quantity of PMs.

While [8] suggests that full disassembly remains economically viable, it appears it does not account for the recovery of magnets alone, rather it stops at the spindle motor assembly. Hence, it is reasonable to conclude that in the context of profit maximization, the PCB is the only component of the two that warrants extraction. The difficulty of removing the motor itself discourages its recovery, and due to the low mass concentration of magnets within, shredding the entire motor is also considered impractical.

4. Conclusions and Future Steps

The growing reliance on REEs for key technologies in the energy transition underscores the urgent need for secure and sustainable sourcing strategies. As Europe faces increasing risks in the supply of these critical materials, recycling practices emerge as one of the few feasible paths to achieving greater self-sufficiency. In this context, design for disassembly has become a pivotal concept to overcome the high European labor costs and the limited adoption of automated disassembly systems. However, in cases where a product is in the later stages of its diffusion curve, a shift of the focus from design-driven approaches to the optimization of existing disassembly processes may be considered.

The recycling of NdFeB permanent magnets from HDDs fits within this last framework. The optimization of HDD disassembly processes enhance the profitability and efficiency of magnet recovery, resulting in a valid solution both for direct reuse and recycling. In other terms, the case study aims to serve as a starting point for identifying different HDD types and adopting the respective best practices for disassembly. Also, the applied methodology could be further expanded to consider the recovery of other REEs in addition to Nd and Dy present in the magnets, with further evaluation of PCB boards and more broadly including 2.5” HDDs.

Nonetheless, an excessive focus on HDDs may yield diminishing returns due to the gradual decline in their usage. For this reason, the European project HARMONY, is studying disassembly processes and their optimization for products with growing demand trends. An example includes the electric motors embedded within the wheels of electric scooters, but the topic can be extended to further items like electric motors coming from automotive and wind turbines.

Finally, following the results obtained and the methodologies proposed, future studies should ideally advance in this direction. The primary objective should therefore be the minimization and optimization of activities, exclusively focusing on essential tasks for the recovery of target components. At the same time, automating downstream processes based on the preliminary identification of specific product configurations should be strongly considered for industrial application.

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