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Streamlining Virtual Product Teardown in Engineering Education Through Affordable Reverse Engineering Technologies

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Abstract. Traditional product teardown exercises, while educationally valuable, are resource-intensive and environmentally unsustainable. By leveraging affordable 3D scanning and CAD modeling tools, an approach is proposed for the creation of virtual product replicas that can be used to reduce costs, environmental impact, and logistical constraints of product teardowns. Two case studies—a leaf blower and a hand mixer—demonstrate the effectiveness of the methodology. The case studies also demonstrate that 3D scanning is particularly advantageous for capturing complex geometries, while CAD modeling is more efficient for simpler components with straightforward geometries. The integration of both techniques ensures that the strengths of each approach are maximized, leading to substantial time savings in creating assembly models. The study confirms that high-quality 3D models for virtual product teardowns can be created using a combination of affordable reverse engineering approaches, making it a viable solution for educational settings.

Keywords: Product Teardown, Design Education, Reverse Engineering, 3D CAD Model, Function Modelling
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1 INTRODUCTION

Product teardown is a critical component of engineering design education, offering students invaluable insights into the functionality and composition of various electromechanical products, such as power tools and small household appliances [1]. Functional models, which result from analyzing torn-down products, provide descriptions of technical systems in terms of the functions and subfunctions required to achieve the overall purpose [2-3]. Functional modeling has thus been ingrained across many engineering design curricula [4], enhancing students' understanding of how technical systems work, aiding in decomposing complex engineering problems, and planning the development of new systems. By combining product teardown and functional modeling, students develop the ability to correctly identify systems' functions, leading to versatile systems thinking skills [5].

These exercises are traditionally performed through the physical disassembly of products, typically at the end of their life cycle. As such, product teardown demands significant resources, including a dedicated workshop space, tools, supervision, and the physical products themselves. The financial burden, coupled with the inherent limitation of a one-time use of products that often become unusable post-disassembly, emphasizes the inefficiency of this traditional method. Another significant challenge is the lack of repeatability and sustainability. Each academic year, educators face the daunting task of replicating the teardown exercises for new cohorts of students, which is both resource-intensive and environmentally taxing.

For instance, Ogot et al. [6] report that at Penn State University, product dissection is a core component of their 1st-year seminars, necessitating the repeated purchase and preparation of consumer products like electric toothbrushes and coffeemakers. Similarly, at the University of Texas at Austin, the reverse engineering course requires the teardown of 40–50 electromechanical products annually, demanding substantial financial and logistical support to maintain the hands-on learning experience, and additionally, at Virginia Tech, maintaining a 1200-student course with product dissection incurs nearly $5000 per year in support costs, highlighting the significant financial investment required to sustain these exercises [6]. These challenges raise questions about the long-term viability of physical product teardowns in educational settings.

In response to these challenges, this paper proposes a shift towards a virtual teardown, leveraging the advancements in digital technology. The virtual teardown, facilitated through the disassembly of detailed 3D models, offers a sustainable, repeatable, and flexible approach. It is argued that the teardown of virtual products reduces the logistical constraints and costs associated with physical teardowns, enabling a more inclusive and accessible learning experience for students. Moreover, virtual teardowns address sustainability concerns by minimizing the need for physical resources and reducing environmental impact, making them a cost-effective and environmentally friendly alternative to traditional methods [7].

Virtual approaches to the analysis of physical artefacts have already been tested in various domains [8-9], including engineering design [10]. For example, LaRocco and Paeng [8] conducted a functional analysis of two 3D-scanned antique weapons, demonstrating how 3D scanning and digital modeling can facilitate safe functional analysis of fragile items, providing insights into their design and usage. In a comprehensive study on reverse engineering, researchers detailed the reverse engineering process through the disassembly of a one-time-use camera, showcasing how this methodology aids in understanding product functionality [10]. The study emphasized the integration of digital tools for capturing and digitizing product data, which facilitates the development of detailed CAD models, thus promoting consistency and reusability of design information and enhancing the overall educational experience [10].

However, despite their advantages, virtual teardowns hinge on the availability of high-quality, detailed 3D models that accurately represent the real-world products, both in geometry and texture. The main challenge lies in the scarcity of models which exhibit the right amount of complexity required for understanding product functionality. For example, the existing online 3D model libraries normally provide merely superficial models of products' exteriors, without the necessary textures or internal components. Additionally, the available 3D models are often not directly compatible with standard CAD software used by the students, meaning that they would have to either learn new software, or convert the models into formats that can be opened using CAD systems, which in return, may results in errors and wrong representations. Therefore, if the creation of high-quality models wants to be scaled up for use across several generations and hundreds of students, there is a need for an efficient and affordable way to reverse engineer products' geometry and texture.

Addressing this gap, the presented research focuses on the development of an affordable and accessible reverse engineering methodology to create comprehensive 3D CAD models which can be used for virtual product teardown. The methodology is intended for both educators and students, who can apply it to digitalize product assemblies for sustainable, scalable, and effective execution of product teardown and function analysis. To meet this goal, two research questions are posed as follows:

- Can high-quality 3D CAD models for virtual product teardown be xcreated using affordable reverse engineering approaches?
- Which affordable reverse engineering approaches are the most efficient for components with specific geometry and texture?

The paper is structured as follows: the methodology is first described in section 2 and then its use is showcased through two case studies in sections 3 and 4. The results are discussed in section 4, followed by the conclusion in the last section.

2 METHODOLOGY

Previous experience in both physical and virtual product teardown was instrumental in identifying and formulating the main requirements necessary for developing the reverse engineering methodology. The following requirements must, therefore, be met to enable satisfactory and accessible replication of product teardown in the virtual environment:

- The methodology should be feasible using affordable and easy-to-use hardware and software.
- The methodology should not require proficient use of hardware and software, ensuring it is accessible and beginner-friendly for users with varying levels of technical expertise.
- The final models must be structured as assemblies with separable components and allow for error-free import and manipulation in 3D CAD software.
- The methodology should be applicable to products of different shapes, sizes, and materials.
- The virtual components in the final model should closely resemble their real counterparts in form and color/texture, ensuring overall visual similarity rather than prioritizing geometrical precision and accuracy.
- Local geometrical precision is critical for interfaces between components and should clearly reflect their degrees of freedom in relation to the rest of the product assembly.

As mentioned in the introduction, the core idea of the proposed methodology is to engage students and educators in creating a 3D CAD assembly model of a product through a combination of reverse engineering techniques. This includes the use of affordable 3D scanning devices (both handheld and tabletop – depending on their availability), photography, and 3D CAD modeling. The modelling involves three primary steps: (1) obtaining the components' geometrical models, (2) the application of color and/or texture, and (3) assembly of components into the final model. The simplified overview of the methodology in the form of a workflow is shown in Figure 1.

2.1 Step 1: Obtaining Component Geometry

For some components, it must first be checked whether their 3D CAD model is already available. This is typically the case for some standard and off-the-shelf components. If such a model exists, it is downloaded for the corresponding library (local or online). When no model is available, its geometry must be reverse-engineered. To do this, the user first assesses the complexity of the component. For components that are simple and easily modeled, reverse engineering is conducted by modelling the component within a 3D CAD system. According to Buonamici et al. [11], such a process typically starts with measurements performed on the physical object. Depending on the object's dimensions, required accuracy, and available tools, different techniques are used to extract and process the necessary data.

However, in most cases, the abovementioned criteria are not met, meaning that the component's geometry is too complex to be modelled from scratch. In these cases, 3D scanning (or photogrammetry as an alternative) must be employed. The user begins by selecting the appropriate scanner based on the component's weight and surface characteristics, using a rotating table for lighter components and a stable surface or handheld scanning for heavier ones.

Transparent, reflective, or black surfaces are treated with a scanning spray to ensure accurate data capture. They then plan the scan orientations to capture all features and ensure proper alignment of point clouds, stabilizing the component with tools like clay if necessary.

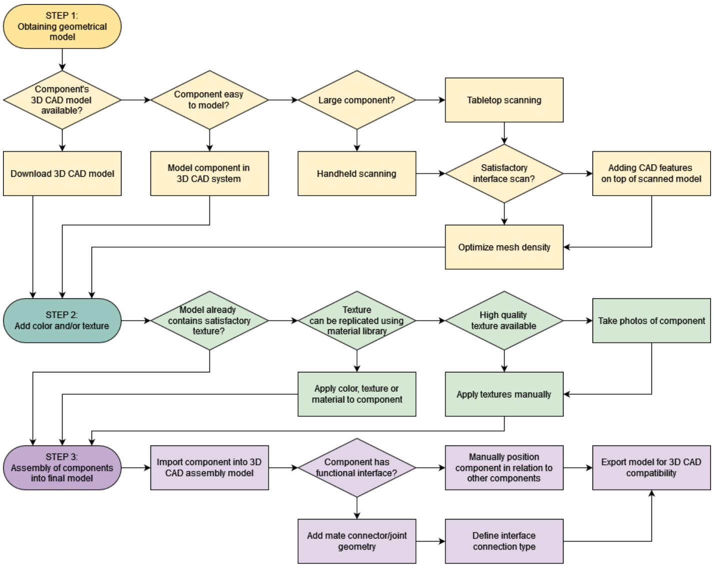

Figure 1: Overview of the proposed reverse engineering methodology.

During the scanning process, they select appropriate tracking methods, ensuring continuous tracking by maintaining visibility of markers and/or distinctive features. For rotational scanning, typically, a single full rotation suffices. After scanning, the user merges the individual point clouds and removes extraneous points and noise. They align the point clouds precisely and reconstruct the mesh with the desired level of detail (see Figure 2). Data alignment and the selection of a convenient starting point for reconstruction are highly important, as they can significantly influence subsequent operations [11]. If any parts of the object are not captured, the user makes manual adjustments to fill in gaps, ensuring the model is complete. Finally, the geometric model, which is ultimately a mesh, can be optimized for better performance, without significantly affecting the component's appearance.

While this paper cannot delve deeper into the specifics and best practices of 3D scanning, the process is already sufficiently studied and documented across various other sources. Wang et al.'s [12] framework for 3D model reconstruction in reverse engineering involves several key processes, including mesh denoising, mesh segmentation, feature reconstruction, and the assembly of primitive features into the final model. Hence, if the initial scan does not effectively capture certain features, such as holes or ribs, additional manually modeled CAD features are added on top of the scanned model to refine the representation.

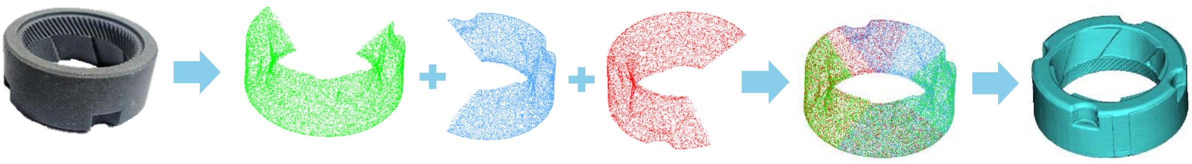

Figure 2: Aligning and merging point clouds to precisely reconstruct a component's geometry.

In rare cases, when the mesh model exhibits substantially low quality, it must be completely remodeled using traditional features or surfaces. In its simplest form, the reverse engineering process from 3D meshes to CAD models involves the extraction of geometric primitives, such as spheres, cylinders, and cones) from the 3D mesh and computing the parameters that give the best fit [13]. It must, however, be noted that the full feature-based recreation of CAD models, which typically occurs as part of the reverse engineering process, is not necessary in this case. Namely, as mentioned earlier, the primary purpose of the 3D models is to support virtual product teardown and functional analysis rather than redesign, remanufacturing, inspection, or replication [14].

2.2 Step 2: Application of Texture and Color

The texturing of the final component model is contingent on the capabilities of the scanning equipment. Scanners that can capture color information directly integrate this into the model, closely replicating the original texture. When color capture is not possible, or if the component has been treated with matting spray (if they have dark, transparent, or shiny surfaces), textures are manually applied after scanning. If the component has a uniform color or texture which is available in the CAD system's library, it can be applied directly to the model. If this does not provide satisfactory results, one must acquire or take photographs of the component from different angles and manually apply them as textures (i.e., as decals), as shown in Figure 3.

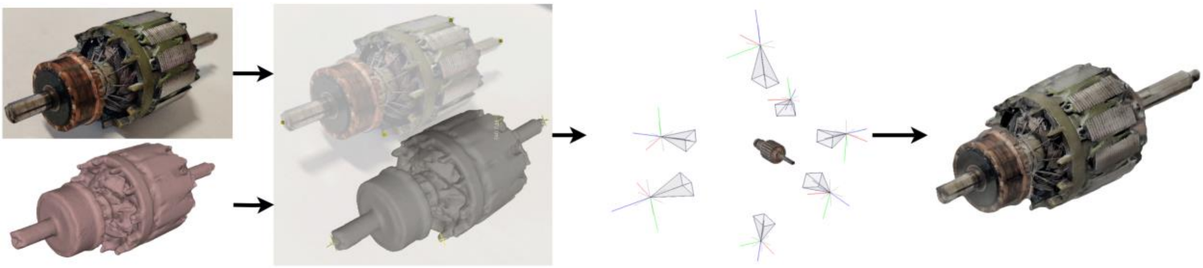

Figure 3: Texturing of the component model using photographs taken from different angles.

For accurate texture mapping, it is crucial to ensure the correct alignment of photographs with the 3D model. This involves capturing multiple images of the component from different angles and ensuring uniform lighting conditions to avoid shadows and reflections that could distort the texture. Post-processing techniques can be used to correct color variations between different textures, ensuring a smooth and continuous appearance across the entire model [x15]. The process includes using specialized software to align the images with the mesh, creating a seamless texture that accurately represents the component's appearance. Additionally, the texture should be applied in such a way that it reflects the material properties of the component, such as glossiness or roughness, to enhance the realism of the virtual model.

2.3 Step 3: Virtual Product Assembly

The final step involves assembling the individual components into a comprehensive assembly model, ensuring that the components are correctly positioned, and mate connections or joint geometry are defined for components with functional interfaces and specific degrees of freedom.

Each component should be defined as a derived component of the original file containing only one mesh. These components include construction geometry at the contact points with other components, ensuring accurate alignment and behavior of the assembly, as shown in Figure 4. Establishing geometric constraints and ensuring the correct interpretation of the scanned data are vital for accurate reconstruction [11]. Additionally, solid and surface feature-based strategies can be applied to reconstruct primitive assembly features and perform boolean and surface trimming operations to assemble the final model [12].

It is also possible to derive other assemblies within the main assembly, achieving the desired tree structure of components. This hierarchical approach allows for better organization and management of complex assemblies, facilitating easier modifications and updates.

Finally, the model should be verified for accuracy by comparing the assembled virtual model with the physical product, ensuring that all components are correctly positioned and that their interactions are accurately represented. This creates a final replica of the product that is ready for virtual manipulation and teardown.

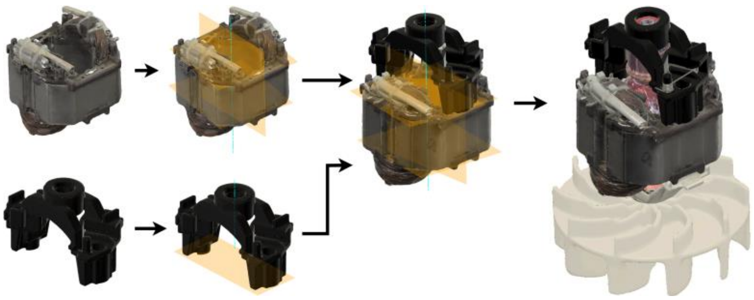

Figure 4: Alignment of components using reference geometry.

The proposed reverse engineering methodology was tested for two different product examples – a leaf blower and a hand mixer. These two products consist of components of different shapes, sizes, and surface finishes, enabling the answering of both research questions.

3 CASE STUDY 1: LEAF BLOWER

The first product selected to demonstrate the practical application of the proposed reverse engineering methodology was a leaf blower (Figure 5, left). It is a relatively complex electromechanical device comprising multiple components, such as the motor, housing, and control switches, each offering a unique scanning and modeling challenge that would effectively test the robustness of the proposed methodology. As such, this first case study primarily aims to answer the first research question posed in the introduction, that is, whether affordable reverse engineering approaches can be used to create high-quality 3D CAD models for virtual product teardown.

The case study involved an engineering design student who undertook the task of modeling the product using a combination of 3D scanning and CAD modeling techniques. The student utilized various affordable scanning devices available at the Design Laboratory – CADLab of the Faculty of Mechanical Engineering and Naval Architecture, including the Scan Dimension SOL PRO, Creality CR-Scan 01, Revopoint POP 2, and Tupel 3D Dental. These devices were chosen based on the size and complexity of the components to be scanned, employing structured light technology and laser triangulation for capturing the geometrical data of the product's components. Each scanner was selected for its specific strengths: the SOL PRO for its high precision, the CR-Scan 01 for its flexibility in handling different component sizes, the Revopoint POP 2 for its ease of use, and the Tupel 3D Dental for its exceptional accuracy in capturing small, detailed parts. The affordability and ease of use of these devices makes them appropriate for scalable use across educational settings (schools and universities).

In addition to the scanning equipment, the student utilized standard computing hardware to handle the demands of the 3D scanning and modeling processes. For processing the point cloud data, surface reconstruction, and texturing, the student used Meshlab software, while for assembly creation, mesh optimization, and sharing of the final model, they employed Autodesk Fusion 360.

The cross-section of the final model is shown in Figure 5, right. Examples of components and how they were reverse-engineered for the purpose of product teardown are shown in Table 1.

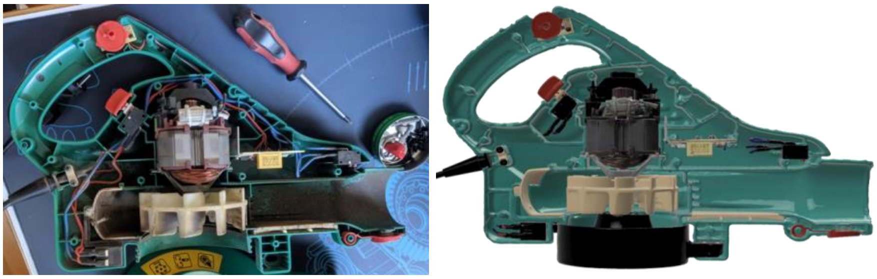

Figure 5: Partially disassembled physical product on the left and its virtual replica on the right.

The leaf blower assembly was divided into four main subassemblies: housing, switches, filter, and drive assembly. Each subassembly was created by importing individual components into Fusion 360 and defining their spatial relationships and connections. These were not only visually represented but also functionally structured to reflect the actual product's operation. The components were positioned correctly within each assembly, and connections were made using mate features in the CAD software to replicate the physical interfaces and interactions between parts (see Figure 6). The use of construction geometry and mate features ensured that the final model was both accurately assembled and functional, closely mimicking the structure and behavior of the physical product in a virtual environment.

Where components interfaced with each other, construction geometry was used to define the precise location of contact and the degrees of freedom necessary for realistic movement within the assembly. The student ensured that each component was fixed in space and derived other subassemblies to achieve the desired component tree structure within the assembly model. For example, the housing subassembly required precise alignment of the upper and lower casings, ensuring that all fastening points and mating surfaces were accurately represented. The switch subassembly involved integrating the electronic components with the housing, modeling the internal wiring, and ensuring that the switch's movement was correctly constrained. The filter subassembly included the detailed modeling of the mesh filter and its interaction with the airflow pathway. Finally, the drive assembly, which consisted of the motor, impeller, and associated components, required careful attention to the rotational degrees of freedom and the accurate representation of the motor's mounting and connection points.

Physical component	Specification	Process	Virtual component
	50 x 55 x 60 mm, matte surface	Scanned on a rotary table, groove added in CAD system, material color applied from the CAD system’s library	
	Ø50 x 155 mm, reflective surfaces, different materials	Pretreated with matte spray, scanned on a rotary table, photographed, and manually textured	

	460 x 110 x 300 mm deep grooves and ribs, combination of dark and reflective surfaces	Pretreated with matte spray, hand scanned with two scanners (faster for global geometry and slower for detail features), photographed and manually textured	
	40 x 30 x 25 mm, reflective surface	Pretreated with matte spray, scanned on a rotary table, original mesh density retained for textured labels, material color applied from the CAD system's library	
	90 x 35 x 35 mm, flexible component, dark and reflective surface	Pretreated with matte spray, scanned on a rotary table, pins and cable modelled in CAD system, material color applied from the CAD system's library	

Table 1: Examples of leaf blower components and associated reverse engineering processes.

Figure 6: Construction geometry and mates are used to define component interfaces and interactions.

4 CASE STUDY 2: HAND MIXER

The second product selected to test the proposed methodology was a hand mixer, a household appliance comprising a relatively small set of diverse components. The goal of the second case study was to compare the efficiency of CAD modelling and 3D scanning when it comes to reverse engineering components for the purpose of the virtual teardown. Hence, all components were both manually modeled and scanned using the same devices as in the first case study. Such a comparison enables the evaluation of how each reverse engineering approach handles different types of components, such as housing, fasteners, motors, gears, and beaters. Therefore, the second case study will help answer the second research question, that is what approach is the most efficient for components with specific geometry and texture?

The student utilized the same affordable 3D scanning devices as in the first case study; they also used Fusion 360 for CAD modeling and for the assembly of final models (both the feature-based CAD models and the mesh models). The procedures of both approaches were the same as in the first case study, and the two final models are shown in Figure 7. It can be argued that the both final models sufficiently resemble the physical product's appearance, structure and behavior.

Figure 7: Cross-sections of virtual replicas of the hand mixer assembled from 3D scanned mesh components (left) and CAD-modeled feature-based components (right).

Since both final assembly models are of similar quality and could potentially be used for virtual product teardown, it is possible to compare the time it took for their creation. Such an analysis can be performed at the overall assembly level as well as for individual components. An overview of the duration it took to create and texturize a 3D CAD model of a component versus the time it took to 3D scan, prepare, and texturize a mesh model of the component is shown in Table 2. The comparison of the two approaches is presented in percentages, where the duration of the 3D scanned model preparation is taken as a baseline. The percentage cells are color-coded to highlight the difference – green when 3D scanning is faster and red when CAD modeling is faster. The table also contains the time it took to assemble the components into two main subassemblies: the base assembly and the beater assembly.

The results provide a clear indication of the efficiency differences between 3D scanning and CAD modeling for various components of the hand mixer. Overall, the total time taken to prepare and texturize the 3D CAD models of all components was 643 minutes, whereas the time for 3D scanning, preparing, and texturizing the mesh models was 413 minutes. This demonstrates a substantial time-saving advantage of 56% with 3D scanning.

Component name	Component model preparation in minutes		3D scanning vs. CAD modeling
	3D scanning	CAD modeling	
Base bottom housing	21 (Pop2)	35	-67%
Base top housing	16 (Pop2)	61	-281%
Rotor	14 (Pop2)	63	-350%
Stator	15 (Pop2)	24	-60%
Bottom bearing	14 (Pop2)	111	-693%
Top bearing	9 (Pop2)	70	-678%
Mount gasket	14 (Tupel)	2	86%
Coupling imbus	8 (Tupel)	5	38%
Rubber feet	20 (Tupel)	6	70%
Interface	22 (Tupel)	16	27%
Brushes	10 (Tupel)	2	80%
Switch	25 (Tupel)	12	52%

Switch clip	17 (Tupel)	4	76%
Power cable clip	22 (Tupel)	13	41%
Base assembly	**50**	**37**	26%
Beater top housing	21 (Pop2)	52	-148%
Beater bottom housing	17 (Pop2)	27	-59%
Beater	25 (SolPro)	47	-88%
Gear	55 (Tupel)	18	67%
Worm gear	18 (Tupel)	33	-83%
Stopper	18 (Tupel)	5	72%
Rubber coupling	17 (Tupel)	4	76%
Beater assembly	**20**	**9**	55%
Total	**413**	**643**	-56%

Table 2: Overview of the time it took to prepare models using the two approaches.

For most components, 3D scanning proved to be significantly faster than CAD modeling. For example, the base bottom housing took 21 minutes to scan compared to 35 minutes to model, resulting in a 67% time-saving. The base top housing required 16 minutes for scanning versus 61 minutes for modeling, indicating a 281% efficiency gain with scanning. Similarly, the rotor and bottom bearing showed even more pronounced differences, with scanning taking 14 minutes versus 63 minutes (350%) and 14 minutes versus 111 minutes (693%), respectively. These results clearly show that 3D scanning is particularly advantageous for capturing complex geometries quickly and efficiently. Examples of such components are shown in Figure 8

However, some components demonstrated that CAD modeling can be more efficient than 3D scanning. For example, the mounting gasket and rubber feet took 14 and 20 minutes to scan but only 2 and 6 minutes to model, respectively, indicating an 86% and 70% efficiency gain for CAD modeling. This suggests that simpler components or those with straightforward geometries might be more efficiently handled through traditional CAD modeling. Examples of such components are shown in Figure 9.

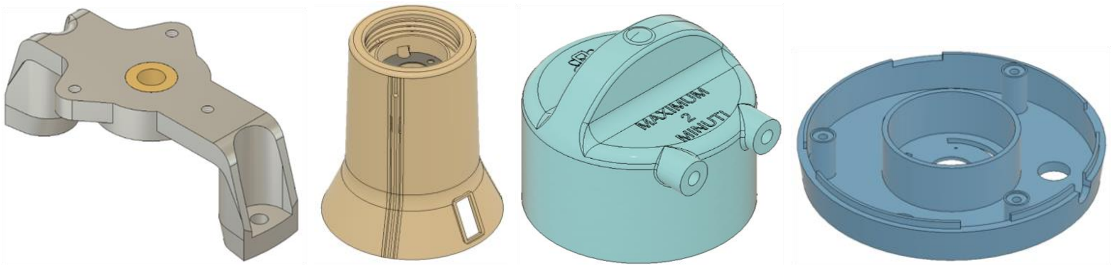

Figure 8: Examples of components for which the 3D scanning approach was faster.

In this example, the components with a more complex geometry were also the bigger ones and were thus scanned using Pop2 and SolPro scanners. On the other hand, the simpler components were dominantly smaller and were scanned using the Tupel scanner.

When considering the overall assembly time, the total time for the creating the base assembly model was 50 minutes for scanning versus 37 minutes for CAD modeling, showing a 26% time-saving for CAD modeling. Similarly, the assembly of the beater model took 20 minutes for scanning versus 9 minutes for CAD modeling, indicating a 55% efficiency gain for CAD modeling.

These findings suggest that while 3D scanning may be quicker for individual components, the precision and pre-defined constraints available in CAD modeling can streamline the final assembly process.

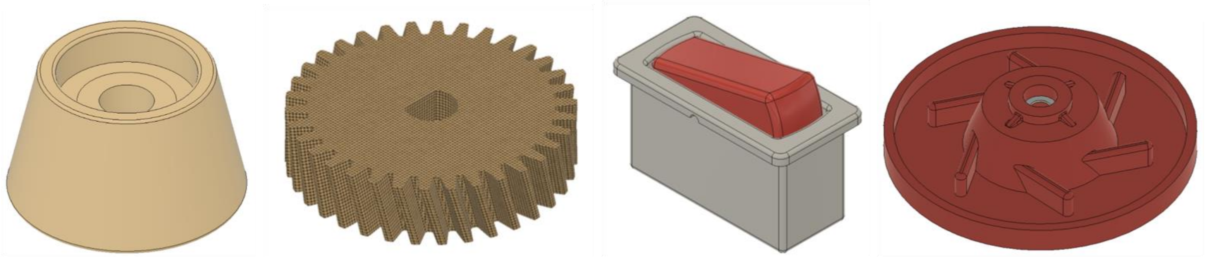

Figure 9: Examples of components for which the CAD modeling approach was faster.

Based on the analysis of the times required for 3D scanning and CAD modeling of each component of the hand mixer, it is evident that selecting the fastest approach for each component results in significant time savings. By choosing the more efficient method for each part—whether it be 3D scanning or CAD modeling—the total time required to create the final model is substantially reduced. Specifically, if we take the fastest approach for each component, the cumulative time required is 303 minutes. This is a considerable reduction compared to using a single method for all components, emphasizing the benefits of a hybrid approach emphasized in the proposed methodology, which leverages the strengths of both 3D scanning and CAD modeling.

5 DISCUSSION

The main purpose of this study was to propose and test a methodology for the creation of high-quality 3D models using affordable reverse engineering technologies that could be used for virtual product teardowns and functional analysis in engineering education. Although there is a large body of research related to reverse engineering, there is limited work specifically addressing reverse engineering for the purposes of product teardown and functional analysis in engineering education. Namely, these applications pose significantly different requirements on the final models compared to traditional reverse engineering, such as the need for models that are not only necessary highly geometrically accurate but rather carry sufficient information about their structure, function and intended behavior. As such, the study aimed to address two research questions, as discussed in the following subsections.

5.1 Creating 3D Models for Product Teardown Using Affordable Reverse Engineering

The first research question investigated whether high-quality 3D CAD models for virtual product teardown can be created using affordable reverse engineering approaches. The findings from the leaf blower case study demonstrated that it is indeed possible to create detailed and functional 3D CAD models using a combination of affordable 3D scanning devices and CAD software.

The case studies utilized a variety of affordable 3D scanning devices, which successfully captured the detailed geometrical data necessary for creating accurate virtual models. The effectiveness of these scanners aligns with findings from other studies that highlight the efficiency of modern 3D scanning technologies in capturing complex geometries and producing point clouds and meshes of satisfactory quality. For example, research by Shah et al. [16] emphasizes the effectiveness of point clouds and 3D scanning in capturing complex geometries in mechanical assemblies. This approach allows for the reconstruction of parametric CAD models, which are essential for accurate functional analysis and virtual teardowns. The study demonstrated that 3D scanning technologies, such as structured light scanners and laser triangulation scanners, are particularly effective for components with intricate surfaces and complex shapes.

While the study demonstrated the feasibility of creating high-quality models using affordable tools, it also highlighted some challenges. The accuracy of the scanned models depends on several factors, including the quality of the scanning equipment and the skill of the operator. The average deviation for entry-level scanners is relatively high, which is generally acceptable for educational purposes but may be a limitation for more critical applications. Advanced scanning solutions offer higher accuracy and better real-time feedback, which could mitigate some of these issues but at a higher cost [17]. Therefore, there is a trade-off between affordability and precision that must be considered when selecting scanning equipment for educational use.

Finally, the integration of 3D scanning data into CAD software, such as Autodesk Fusion 360 used in the study, is a critical step in the reverse engineering process. Modern CAD software often includes features that facilitate the import and manipulation of scan data, enabling the creation of detailed and accurate models. This workflow is essential for ensuring that the final models are both functional and representative of the physical products. The integration with CAD software is also convenient for the frequent cases where additional features must be added manually to the meshed models, such as deep holes and grooves. The combination of scanning and subsequent CAD modeling, as demonstrated in this study, aligns with the widely accepted workflow in both academia and industry [18-20]. Moreover, for the components of simpler geometry, 3D scanning might be needless, as such a geometry could easily be recreated using traditional 3D CAD modeling. The frequency of such cases was investigated in the second case study.

5.2 Comparing the Efficiency of 3D Scanning Against CAD Modeling

The second research question aimed to identify the most efficient reverse engineering approaches for components with varying geometry and texture. The hand mixer case study compared the efficiency of 3D scanning and CAD modeling for different components, providing insights into the strengths and limitations of each approach. This subsection expands on these findings by incorporating relevant research and industry practices to provide a comprehensive understanding.

As expected, the case study confirmed that 3D scanning is generally more efficient for components with complex geometries, while CAD modeling is better suited for simpler parts. For instance, components such as the rotor, stator, and bearings, which have intricate details, were more quickly captured using 3D scanning. On the other hand, simpler components like the mount gasket and rubber feet were more efficiently modeled using CAD software. Similar findings are reported in various studies and industry practices. For example, 3D scanning technologies, such as structured light scanners and laser triangulation scanners, are widely recognized for their ability to capture detailed geometries quickly and accurately. These technologies are particularly effective for components with complex surfaces and intricate details [16, 21-23].

While 3D scanning offers significant efficiency advantages for complex components, it also presents some challenges. Firstly, the post-processing of scan data, including noise removal and mesh optimization, can be time-consuming and may require specialized software. Secondly, the accuracy of the scan can be affected by factors such as light, surface reflectivity, transparency [24], and the presence of fine details that may not be fully captured. In such cases, 3D modeling might still require more time, but the resulting CAD model significantly better resembles the physical component's geometry – and thus also its function and intended behavior.

CAD modeling is also more efficient for simpler components where precise measurements can be easily obtained and translated into digital models. CAD software allows for precise control over geometric parameters and is well-suited for creating models of components with regular shapes and straightforward features. Another advantage is that manual modeling is less dependent on the physical characteristics of the component, such as surface texture and reflectivity, which can complicate 3D scanning. While CAD software can also be used to reconstruct the model from 3D scan data, this process can often take more time than measuring and modeling from scratch, especially with affordable scanners that may not provide high-quality scans. Additionally, the methodology requires a higher skill level to ensure accurate digitalization and reconstruction.

Given all the above, the study's findings suggest that a hybrid approach, combining 3D scanning and CAD modeling, can maximize efficiency by leveraging the strengths of both methods. It has already been shown that creating a CAD model from 3D scan data is typically faster and more precise compared to taking manual measurements and modeling from scratch [25]. For complex components, 3D scanning can quickly capture the overall geometry, while CAD modeling can be used to refine specific features and ensure accuracy. This approach is supported by industry practices where hybrid workflows are commonly employed to balance the speed and precision of reverse engineering tasks.

6 CONCLUSIONS AND FUTURE WORK

In conclusion, the study confirmed that high-quality 3D CAD models for virtual product teardown can be effectively and efficiently created using affordable reverse engineering approaches. The combination of affordable 3D scanning devices and versatile CAD software provides a viable solution for educational settings, balancing cost and quality. This approach not only reduces logistical and financial burdens but also enhances the sustainability and repeatability of engineering education exercises. The reverse engineering approach encourages decomposition of both physical products (in order to digitalize individual components and their interfaces) and virtual products (to perform functional, structural and other types of analyses). These types of activities are essential in addressing the need for new practices that will motivate engineering students and provide them with skills necessary for the adaption to the everchanging field [26]. Additionally, the proposed methodology is aligned with the trends of incorporating virtual activities in engineering education and addresses the calls for modernizing education through digital technologies (such as digital twins and virtual reality) and digital skills [27].

Further advancements in scanning technology and software capabilities are likely to improve the efficiency and accuracy of these methods, making them even more accessible and effective in the future. Moreover, the potential expansion into virtual reality promises to enhance this methodology by offering a more immersive learning experience. Virtual reality’s inherited compatibility with visualization and CAD tools could significantly elevate students' engagement and foster a deeper understanding, which can ultimately lead to more independent and efficient problem-solving skills [28].

One notable limitation is that the proposed methodology was only tested on two products, which does not represent the full spectrum of intended virtual product teardown applications. Additionally, only one subject participated in the case studies, potentially affecting the generalizability of the results. The quality and accuracy of the 3D scanned, and CAD modeled product replicas, as well as the time allocated to obtain these models, are significantly influenced by the operator's skill and tool mastery. The selection of scanners was also limited to affordable options, which might not capture the full potential or limitations of the available technology. These factors together highlight the need for further validation of the proposed methodology across diverse conditions and with a broader range of users to account for varying levels of expertise.

Future research should focus on validating the generalizability of the proposed methodology with a broader range of products, varying in shape, size, complexity, and surface finish. The following studies should also involve students and educators with different skill levels in CAD modeling and 3D scanning to assess the methodology's accessibility and effectiveness across a wider audience. Doing so will ensure that the methodology is robust and adaptable to various educational settings and technical proficiencies. Investigating the potential for automated post-processing techniques could also reduce the time and skill required for preparing the final models, making the methodology more efficient and user-friendly.

Finally, developing a library containing the first batch of reverse engineered models could provide valuable resources for educational purposes and streamline the integration of virtual product teardown exercises into design and engineering curricula. Such a library would also allow for a comprehensive study of functional analysis based on virtual product teardowns, in order to determine whether the students receive the same depth of understanding and practical experience as they would with physical teardowns.

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