A Novel Automated Approach for Geometric Reconstruction and Flexible Remanufacturing of Spur Gears Using Point Cloud Mapping Analysis

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Abstract. In the modern manufacturing era, the atomization of industrial equipment and maintenance activities is a core of industrial evaluation. The growing geometric complexity of products in industrial sectors requires maintaining the reliability and durability of production considering the zero-defect manufacturing concept. In this regard, monitoring product features both during manufacturing and operational processes along with periodical tests and analysis of parts are required. In this study, an automated remanufacturing process of industrial parts via surface point clouds is developed as a step towards smart maintenance. In fact, this flexible remanufacturing method reduces spare part supplying delays. First, a 3D laser scanner is used to provide a numerical 3D representation of industrial spur gear surfaces as a triangulated mesh. Then, using automated geometry recognition on this mesh, a computer-aided design (CAD) model of the scanned part is reconstructed. The geometry of this CAD model is then modified to reinforce the worn gear and to respect gear profile standards. By comparing CAD and scan data, freeform surfaces of this reconstructed CAD model are finally verified and adjusted to meet a set of assembly conditions. This leads to the reconstruction of an optimized CAD model, which is then used to build a gear mold. This mold is fabricated using a MultiJet Printing™ (MJP) plastic additive manufacturing machine. Analyzing mechanical properties of the worn gear, polyurethane as the fabrication material is gravity-casted in a mold and cured. Based on the proposed method, a worn and damaged spur gear of heavy-duty equipment in the mining industry is remanufactured. The equipment is thus repaired by replacing the worn gear with a remanufactured spare gear, which fulfills its nominal performance. It is worth underlying that the proposed approach allows reducing downtime of this equipment from, as estimated, six months to three weeks.

Keywords: 3D laser scanning; geometry reconstruction; CAD; CAM; CAI; Additive manufacturing; Reverse-engineering.
DOI: https://doi.org/10.14733/cadaps.2023.92-108

1 INTRODUCTION

The pillars of maintenance management in industrial sectors are equipment, machinery, and manpower. In order to increase productivity and efficiency in providing services based on established standards, special attention should be paid to increase operational efficiency by reducing repair costs and stopping machinery [9]. The success of organizations in providing services and increasing the product and service quality depends on the maturity of their maintenance implementation through the most appropriate and practical methods. In traditional management, maintenance is considered a supporting facility, which has little advantage for organizations [12]. However, in more recent approaches, maintenance development of mechanical equipment, roads, and buildings is considered an essential part of the operations of an organization [7]. This approach includes the application of effective strategies to maintain significant added value in the activities of any organization. In other words, each system is a set of interconnected and proportionate components that are used for a common purpose. According to this definition, the maintenance system consists of technical personnel, buildings, equipment, tools, spare parts, information, technical documents, working methods, and instructions that are properly put together to achieve stated goals, such as maximizing equipment and operational efficiency while minimizing maintenance and repair costs.

In general, maintenance practices can be classified into three basic systems: breakdown maintenance (BM), total productive maintenance (TPM), and reliability-centered maintenance (RCM). At the beginning of the industrial revolution and the era of mass production, breakdown maintenance systems were common. In those days, downtime was not considered a key performance indicator (KPI). Therefore, breakdowns and sudden stops of machinery did not represent a serious problem for those involved in production. During this period, in the minds of most managers and engineers, preventing the occurrence of defects was not a central issue. Industrial competitions and globalization, as well as custom productions and demands for different variety of products, led to the growth of automation. In the meantime, preventive maintenance (PM) methods were first proposed and implemented in the United States. During the 1950s, preventive practices gradually evolved, and predictive maintenance approaches were introduced in the American industry in 1954. Finally, total productive maintenance (TPM) was introduced by the Japanese industry in the 1970s. This method focuses on the fact that maintenance as one of the most important pillars of factory management is inseparable from lean management tools wherein the total productivity of the plant rests on these pillars [24]. New achievements of maintenance systems and asset management developments in the fourth industrial revolution (Industry 4.0) are the introduction of maintenance systems based on the operating conditions of machines which leads to reliability-centered maintenance (RCM). Increasing investment in industrial machinery and automation on the one hand and increasing their financial and economic value, on the other hand, led to a boom in maintenance, asset management, and occupational health and safety performance. Therefore, managers and industry owners used RCM methods to maximize the useful life of production equipment and extend its economic life cycle. Rapid technological developments have raised the standards of quality assurance, safety, and reliability. Today's organizations can adapt to a new competitive industrial ecosystem by adopting risk assessment and management methods based on Failure Modes, Effects, and Criticality Analysis (FMECA). FMECA is a systematic tool that assesses the criticality of equipment in a plant, which enables identifying breakdowns associated with specific system components and functions. In this technique, the subsystem is usually broken down to the level of components or functions, and by focusing on each specific component or function, malfunctions related to that component can be determined and evaluated [3, 16]. FMECA helps to examine products and processes during the early stages of development to find potential failures and to initiate measures to prevent failures through integrated risk analysis.

In modern manufacturing systems, there is a correlation between maintenance and inspection procedures [5]. As already mentioned, the importance of maintenance in industrial sectors is undeniable. One of the most important steps is to diagnose inspection problems, which requires the use of up-to-date techniques and, for this reason, the use of non-destructive inspection (NDI) is widely considered [15]. Optical and laser geometric evaluations of parts have been introduced, such as 3D laser scanners and coordinate measuring machines (CMM) [18, 26]. Of course, compared to scanners, CMM presents very low scanning speed and difficult planning, which limits its application to large parts. The introduction of 3D scanners in inspection and condition monitoring has been democratized and widely considered in many industrial sectors. The use of 3D scanners for geometric evaluation and operational arrangement optimization has been investigated by many researchers [11, 25, 26]. Pathak et al. used 3D scanners for an inspection planning framework aimed at improving measurement quality for geometrically complex parts [22]. In the recent concept of computer-aided inspection (CAI), 3D laser scanning and reverse-engineering are used together [13, 14, 23]. Meanwhile, with the introduction and expansion of 3D printing methods, it became possible for engineers to design complex parts and fabricate them with fewer restrictions as a prototype or final product [1, 6]. The use of this flexible fabrication method can be observed in, the construction of nature-inspired medical tools, bio-printing, the production of special geometries in architecture, the printing of smart materials and structure, electronic equipment [2, 27]. An important use of 3D printing is for reverse-engineering in which using scanning methods, CAD modeling, and 3D printing can help to recover and optimize the geometry of worn parts and fabricate them in a short delay. Jiang et al. used this hybrid system as a new method to produce natural rock joints by digitizing the surfaces of features of real samples and printing physical molds with high accuracy and quality [10]. With a similar approach, James et al. used photogrammetry as an alternative and practical method instead of 3D laser scanners in reverse-engineering design [8]. Parry et al. also used a combination of 3D laser scanners and fused deposition modeling (FDM) to produce a crutch with a custom hand grip for arthritis patients with a manufacturing time that is under 20 minutes and at a low cost [21].

Maintenance activities in many industrial sectors predominantly focus on asset management based on periodical equipment inspection and parts replacement using statistical tools, e.g., Pareto analyses, distribution analyses, system reliability modeling, etc. These tools allow a rough assessment of parts life, which helps planning maintenance activities to reduce the complete or partial loss of equipment during production. However, these methods show significant drawbacks such as a lack of information regarding spare parts availability and accessibility, and regarding mechanical parts' real remaining useful life. This highlights the importance of detailed mechanical analyses and the importance of being able to remanufacture spare parts based on the geometry of used and damaged parts.

In this work, we present an automated method for remanufacturing used and damaged mechanical parts, which is based on reverse-engineering techniques. In this regard, based on FMECA and root cause analysis (RCA), a used and damaged industrial spur gear made of plastic material is detected as the cause of mining industrial machine downtime. Supplying and replacing the spare part is estimated to be six months due to the fact that the market does not supply the corresponding spare part. To this end, the shape of the worn part is first scanned using a Handyscan 3D™ to acquire the point cloud of surfaces of the part. Then, an STL format of a triangulated mesh is generated based on the acquired point cloud. The reconstructed geometry of this mesh is then obtained in a CAD format wherein the geometric elements and features of the spur gear are represented. The key geometric characteristics of the gear are then verified with respect to geometric standards for gears. Uniform sizes and measuring units (metric versus imperial) are also applied for functional, behavioral, and structural features of the part. The CAD model is then optimized to reinforce the worn and damaged areas on the worn gear to increase its mechanical strength. In order to make sure that the gear fits with respect to its assembly features, such as mounting hole size and location, the optimized CAD model is compared with the wornout gear's scanned model. By comparing CAD and scanned models, geometric deviations of assembly features between the reconstructed CAD model and the real part (worn gear) are identified. These deviations are then minimized iteratively by modifying, step by step, the reconstructed CAD model. This last verification and modification of the modified CAD model minimize geometric deviations of assembly features between the CAD model and the real part (scan of the worn gear), which leads to an optimized CAD model. This optimized CAD model is finally used to fabricate a mold for gravity casting of the new plastic gear. A MultiJet Printing (MJP), plastic-based 3D printer, as an additive manufacturing method is used to fabricate this mold. Capable of printing in an Ultra High-Definition mode, the ProJet MJP 2500™ can print with precision elastomeric parts with true-to-CAD accuracy, superior surface finish, and high-quality edge fidelity for true functional testing which makes it possible to print even smaller features, down to 300 microns or finer.

To the best of our knowledge, there is no study on the automated reverse-engineering of gears based on point cloud mapping along with CAD optimization of gears. Here, the geometric optimization of an industrial gear is performed to solve some problems encountered, e.g., some thicknesses are slightly increased to enhance the resistance of the gear and to distribute force over a larger surface; curvatures of characteristic geometries and right-angle corners are modified to decrease stress concentration. This new approach can be counted as the first step regarding maintenance 4.0 which proposes an efficient strategy towards intelligent manufacturing and production systems.

2 MATERIAL AND METHOD

2.1 Problem Statement

This work aims at recovering the geometric shape of a plastic spur gear used in mining industries, which is worn and damaged. In fact, an old production machine, used in the mining industry, was stopped due to a failure of this gear. The company that built this machine does not exist anymore and the cycle life of the whole machine depends on this gear part. Regarding the maintenance aspect, downtime due to the lack of spare parts is estimated to be at least six months. In this work, root cause analysis (RCA) is performed wherein based on the Ishikawa diagram [17] (as depicted in Figure 1), which is analyzed the cause of wearing and failure of the studied gear with respect to material, methods, environment, means, and measurement. This analysis discloses that gear damage and rupture are mostly carried out where geometric defects and stress concentrations are present, which necessitates geometric recovery and optimization of the part to increase its lifetime.

The main problem of industries located in faraway and isolated sites, such as mining industries in northern regions of Canada, is that supplying spare parts can take a long time, which causes considerable delays in production. In this regard, increasing downtime due to the unavailability of spare parts, especially in isolated and countryside mining, is costly. In order to remedy this problem, we propose a flexible and automated remanufacturing approach to recover the geometry of worn parts and fabricate these parts using additive manufacturing and computer-aided manufacturing (CAM) methods. In this approach, 3D scanners are used to acquire geometric information on parts and to perform reverse engineering. 3D scanners acquire point clouds on part surfaces, which are used to reconstruct tessellated surfaces (usually as a triangulation). Geometric features of parts, as well as geometric specifications, can then be extracted and reconstructed even though the original CAD model and remanufacturing technical information of parts do not exist. Using this method, a part can be reconstructed with higher quality wherein geometric optimization is carried out to improve its mechanical strength, by the way increasing its useful life. The modified and optimized part can then be reproduced using CAM methods or 3D printing, eventually using more durable manufacturing materials. This process, based on 3D scanning, reverse engineering, CAD model optimization, and manufacturing can be used to reproduce a variety of mechanical parts with complex geometries. In general, industrial 3D scanners which are used to precisely acquire the geometry of a part are categorized as laser and optic scanners. Laser scanners use multiplexed sensors composed of a camera along with laser beams to generate a point cloud of the surfaces of a scanned part. As for optic scanners, structured light sources are used to measure the surfaces of an object in the format of a point cloud. Each scanner presents measuring errors in acquired point clouds on surfaces of a part. It is worth mentioning that size optimization of triangulated mesh generated from these point clouds is carried out using mesh smoothing and filtering algorithms. This reduces data-taking and analysis time decreasing measuring errors during the scanning process.

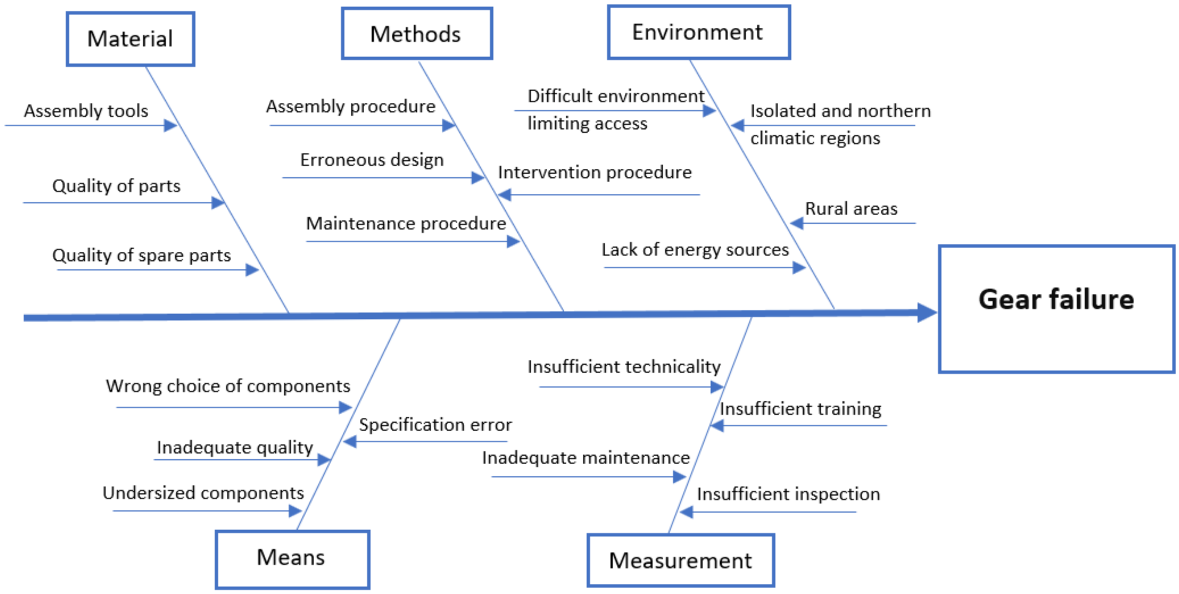
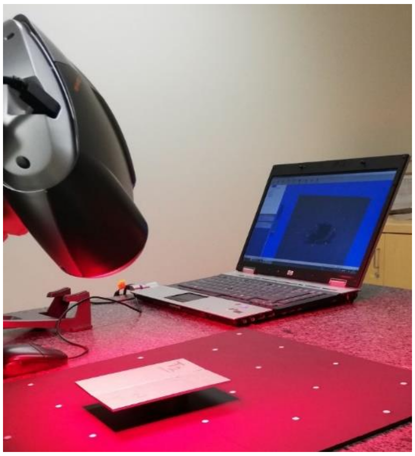
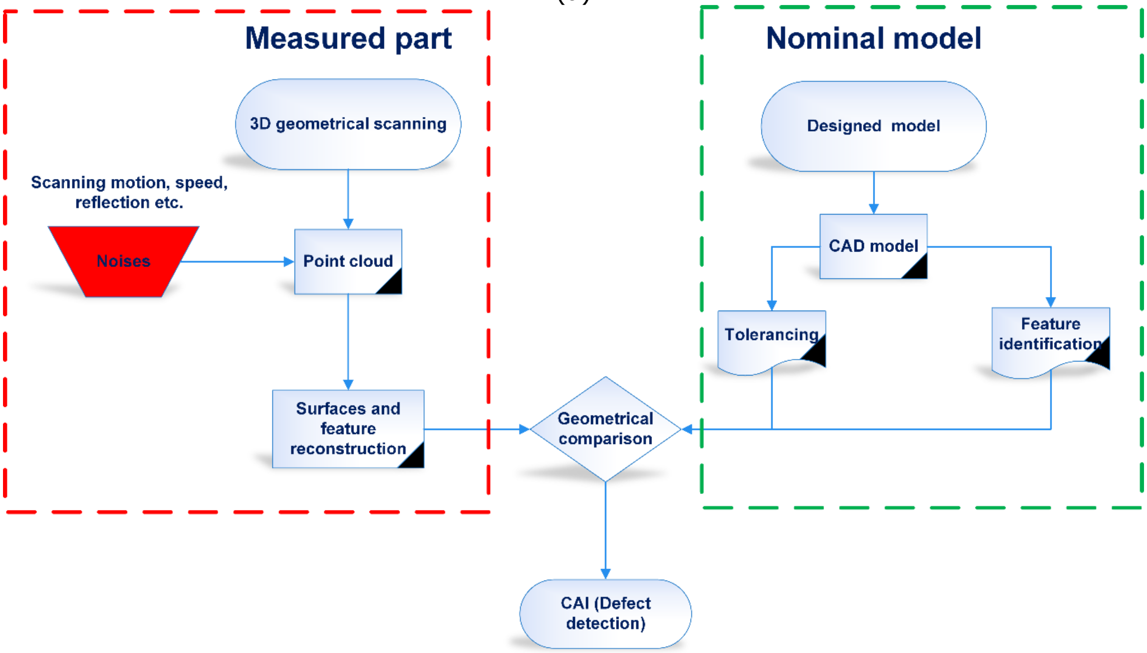


Figure 1: Ishikawa diagram of the maintenance procedure.

Following the geometric reconstruction of a part using 3D scanners, the functional shape of the part which conforms with the quality control measurements and assembly requirements needs to be developed. In this regard, computer-aided inspection (CAI), which is an efficient method for geometric inspection, can be used. To this end, the geometrically optimized CAD model is modified to meet assembly conditions. Utilizing the scanned model of the worn part, geometric deviations of assembly features on the optimized CAD model are identified. This is performed by comparing the geometry of the reconstructed CAD model with respect to the scanned model. Compared to conventional inspection methods, CAI performs a virtual inspection which is less expensive and time-consuming, which reduces human intervention by a large margin. To be more specific on how CAI works, it is worth mentioning that point clouds acquired from surfaces of a 3D scanned part are represented in a measuring coordinate system while the CAD model is represented in a design coordinate system. To compare these models, registration should be employed wherein the CAD and scanned models are brought and aligned in a common coordinate system. A Euclidian distance calculation between surfaces of CAD and scanned models represents geometric deviation between the two models. CAI supports rapid inspection by using color maps to show the distribution of deviation across the whole part. This information can also be used to investigate the details using dimensioning across sections to compare with drawing callouts or Geometric Dimension and Tolerance (GD&T) enabling quality controls related to assemblies. Figure 2.a represents a 3D laser scanner that is used to acquire point-cloud data from surfaces of a part. Figure 2.b depicts a schematic representation of CAI using 3D geometric scanning of parts wherein the objective is assessing geometric deviations of scanned parts with respect to the CAD model with respect to specified tolerances. It is worth mentioning that in CAI applications, the nominal CAD model is usually available to be used as a geometric reference in the inspection. However, in this work, the defective machine is old heavy-duty mining industrial equipment that the supplier does not exist. In this regard, the nominal CAD model of the damaged part is not available. As explained in more detail below, the CAD model built from scanning the worn part plays the role of reference geometry, especially when assessing assembly conditions during the final geometric optimization step (step 6 in the next paragraph).



(a)



(b)

Figure 2: a) Geometric scanning using a 3D laser scanner b) Conventional computer-aided inspection (CAI) methodology based on 3D scanning.

2.2 Methodology

Introducing automation, repeating manufacturing operations such as checking consistency in multi-cavity molds or studying deviation trends using statistical process control by picking out certain critical dimensions over time can be speeded up. Here, an automated remanufacturing approach (as presented in Figure 3) is developed based on reverse-engineering techniques in which the following steps are pursued to recover a used industrial spur gear's geometry and remanufacture it.

- Step1: scanning the worn gear using a 3D laser scanner (Handyscan 3D™) to obtain a point cloud and a triangulation of the part in an STL format.
- Step2: recovering a CAD model from scan data of the gear using geometric reconstruction methods based on the STL format of a part, e.g., in Solid Edge™ software. The result of this geometric reconstruction is presented as Version 1 in
- Figure **8**.
- Step3: modifying the dimensions of the reconstructed CAD model based on feature size and unit normalization. In this step, measuring units (metric versus imperial) and the size of features, e.g., gear teeth characteristic features, mounting holes, filleting radii are normalized. (presented as Version 2 in
- Figure **8**).
- Step4: optimizing the modified CAD model obtained after step3, based on standard geometric characteristics of gears using the American Gear Manufacturers Association (AGMA) standards. (presented as Version 2 in
- Figure **8**).
- Step5: optimizing the modified CAD model obtained in the previous step, based on mechanical strength of the part. In this step, the mechanical strength of the gear is improved by compensating for worn and damaged areas. (presented as Version 3 in
- Figure **8**).
- Step6: verifying the conformity of assembly features in the reconstructed CAD model to comply with assembly constraints of the part and optimizing this reconstructed CAD model with respect to assembly constraints. A CAI approach, based on a geometric comparison between scan and CAD models, e.g., in PolyWorks™, is used to ensure that assembly characteristics and mounting features of the part are consistent. Verifications and modifications are iteratively applied until all assembly features are consistent. The result of this geometric optimization is presented as Version 4 in
- Figure **8**.
- Step7: A mold of the gear, based on the CAD model obtained after step 6, is fabricated in two halves, including fastening features, by additive manufacturing or CAM machining. A post-manufacturing automatic inspection is then applied to identify manufacturing defects in the mold.
- Step8: the gear is gravity-molded, and the remanufactured part built is verified and controlled according to geometric and material characterization. Finally, the part is certificated as quality control validated to ensure the post-fabrication quality control. This certificate can also be used during the part inventory and maintenance 4.0 process.

3 RESULTS AND DISCUSSION

In this work, a worn and damaged industrial plastic spur gear is reversed-engineered based on the method proposed and described in the previous section. This type of spur gear is particularly used in the mining industry wherein old and heavy machines are used for excavation, crushing, and heavy transportation. These machines are generally designed and fabricated in a very reliable manner, which ensures long useful life. However, the effect of wearing parts brings about important challenges in maintenance planning and spare parts management. One of the serious problems in getting spare parts is that suppliers of these special and custom-made machines do not exist anymore and that they do not support the market with their spare parts. This can lead to a long shutdown of production activities, operational and production loss affecting negatively downstream processes development with significant maintenance costs. One solution to this problem is adding stand-by machines and keeping a large number of spare parts that are stored in warehouses and stockrooms.

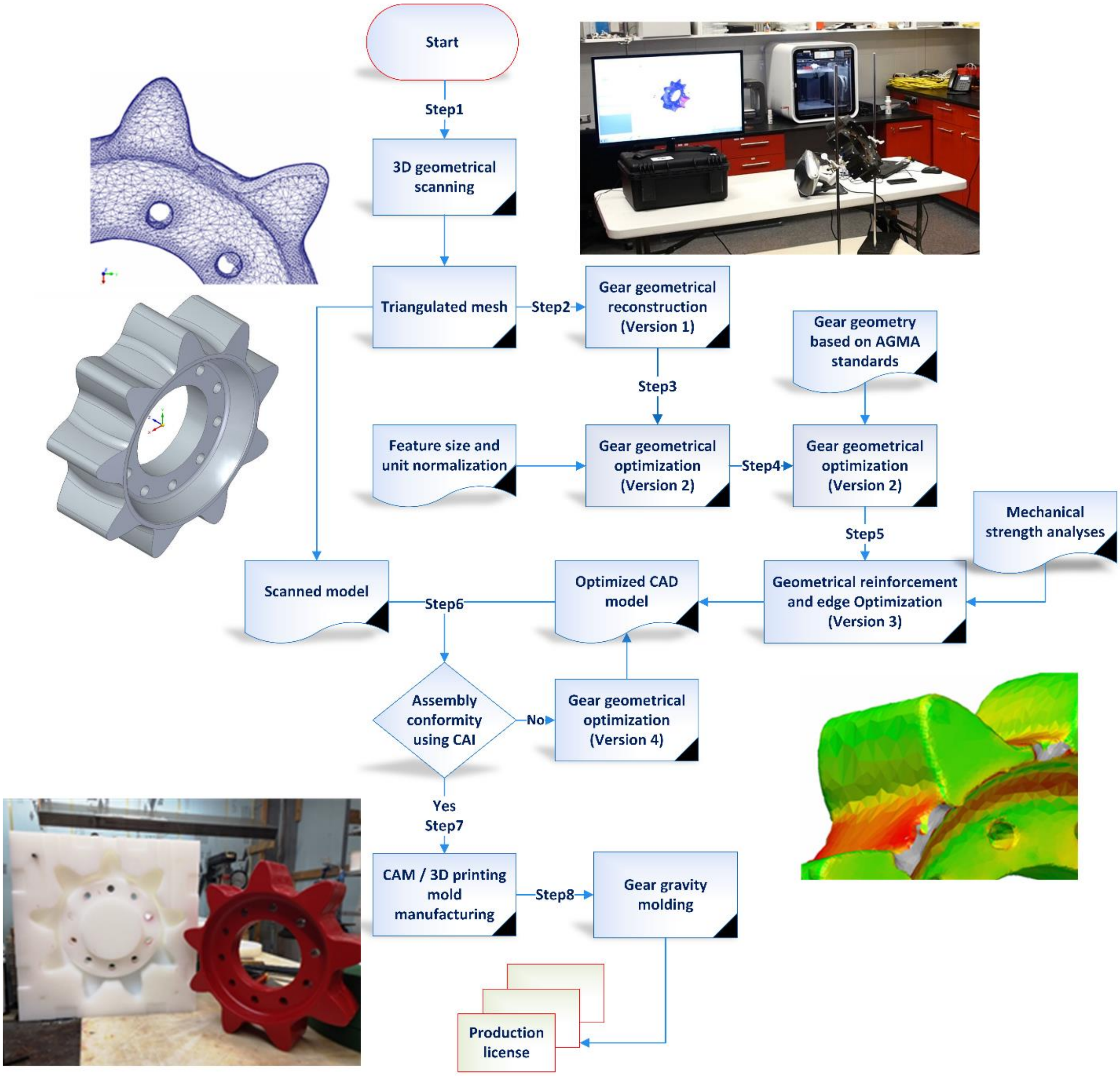
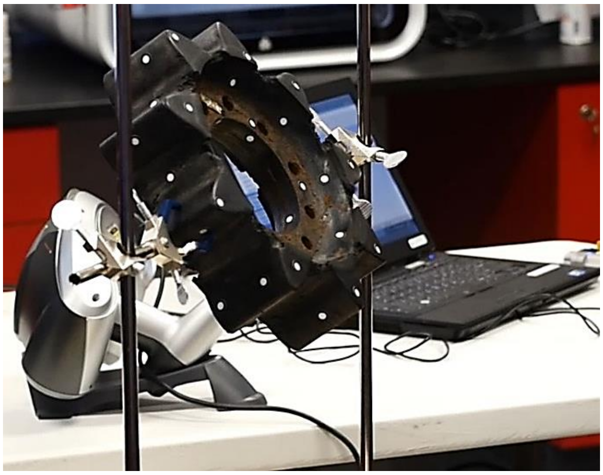


Figure 3: Schematic diagram of the proposed approach.

Nevertheless, stocking these parts, as well as planning and maintenance of standby machines, are very time-consuming and expensive for the maintenance department of these industries. In this context, being able to recover worn parts and provide spare parts in acceptable delays, based on reverse-engineering methods, is an advantageous alternative that can save significant time and reduce maintenance-related costs.

In this section, our proposed method is validated through a comparison between the reverse-engineered CAD-designed model and the scan model of worn industrial spur gear as the reference geometry. As introduced earlier, it is very important to underline that the nominal CAD model of these parts is not available. The geometry of the CAD model is reconstructed from the point cloud of scan data. Therefore, the reference model during geometric inspection based on CAI methods and assembly fitting verification remains the scan data of the worn gear. Dimensions of the spur gear bounding box are approximately 11 1/2 inches in length and width, and 3 5/8 inches thick. In this work, geometric optimization of the CAD model is performed to represent the standard geometry and closest geometric design of the complex shape of the spur gear. Furthermore, based on visual diagnostic and mechanical analysis of the worn gear, damaged areas of the gear are reinforced by adding material, chamfering, and filleting. This is performed by increasing the thickness of material in the CAD model where the worn gear is seriously damaged and by rounding corners and edges to decrease stress concentration. Modifications of this CAD model also take into account assembly geometric limits of the part in the whole system as well as manufacturing issues (gears are manufactured with plastic molding in this case).

To apply the reverse-engineering process proposed in this paper, the worn spur gear is first scanned with a laser scanner (Handyscan 3D™ Creaform) to acquire a point cloud from the surfaces of the part. In Step1 of the process, as introduced in the previous section, a scanning setup and a 3D laser scanner are used to acquire a point cloud of surfaces (see Figure 4.a). Figure 4.b represents a portion of the scanned part during this scanning process. A triangulation (in the STL format) is then generated from this point cloud. This initial triangulation is processed with methods such as mesh cleaning, smoothing, filtering, and simplifying, which is performed to reduce scanning noise and errors and to represent the scan model in detail with an optimized mesh size [23].


(a)


(b)

Figure 4: Scanning process using a 3D laser scanner a) Scanning setup b) Point cloud of a portion of the part during the scan.

Following the 3D scanning of the spur gear, a CAD model is reconstructed in Step2 (gear geometric reconstruction -Version 1 as shown in
Figure **8**). This CAD model fits primitive and complex geometric features to the triangulated facets of the scanned mesh. These features consist of simple points, lines, and surfaces, as well as complex higher-order polynomials-based curves and surfaces such as Non-Uniform Rational B-Splines (NURBS) [19]. Figure 5 shows a geometric representation of the first version of the spur gear CAD model based on scan data. As introduced, some surfaces and primitive features are automatically created with Solid Edge™ (using Reverse Engineering tools) based on tessellated

surfaces (triangulated surfaces) information in the mesh file. Generating more complex shapes such as tooth profiles, beveling and rounding edges, and optimizing feature geometries are manually added to primitive features.

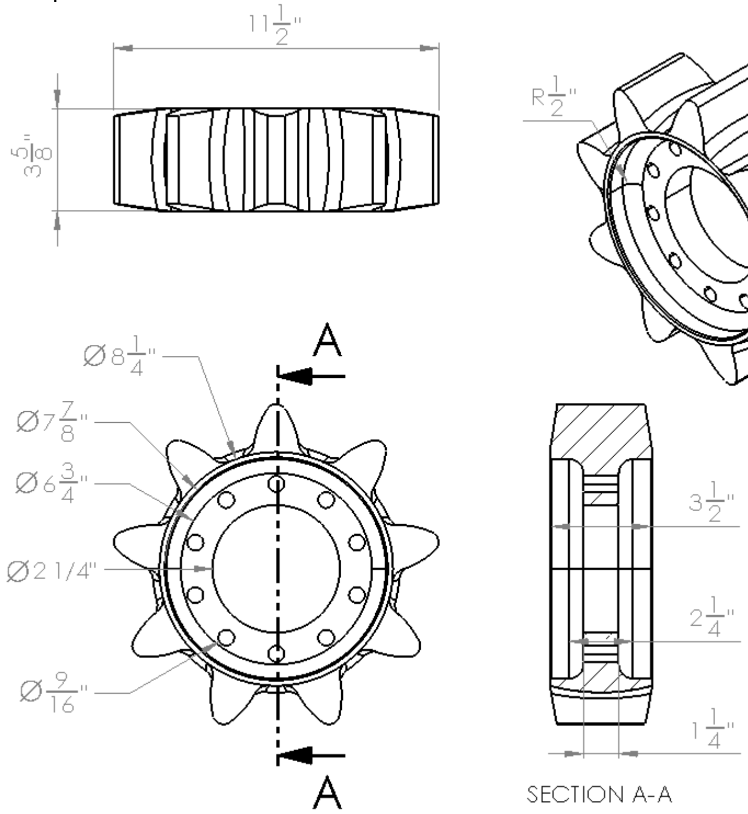
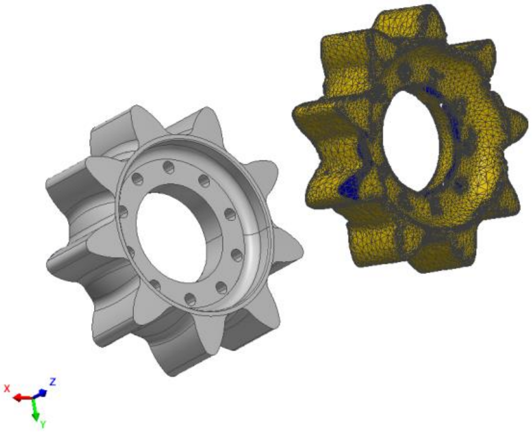


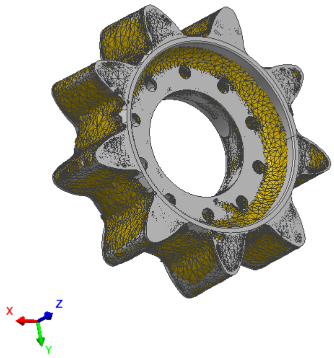
Figure 5: Assessment of normalized dimensional specifications of the spur gear based on scan data (all dimensions are in inches).

Key dimensions such as flank and face dimensions of the tooth as well as the pitch circle, addendum, and dedendum circle diameters are then measured on the optimized mesh file and on the reconstructed CAD model. In Step3, geometric features such as mounting holes and filleting radiuses are also measured, and measuring units of features are normalized. Given that neither dimensional information (detailed drawings) nor CAD information of the nominal gear is available, dimensional units of the features first need to be identified. Applying measure conversions in a trial-and-error approach, dimensions of the gear are identified from the imperial system of units (dimensions are consistent with inches). In Step4, the reconstructed CAD model is optimized to respect the standard geometry of gears, such as defined by the American Gear Manufacturers Association (AGMA) standards. To follow the gear tooth profile, the involute gear profile is used in this study according to the original measurements of the profile on the scanned gear. This optimized geometry is represented as gear geometric reconstruction -Version 2 in Figure 9. In Step5, based on visual analysis, finite elements analysis (FEA), and non-destructive testing (NDT) on the worn part, mechanically vulnerable zones such as damaged areas, fatigue-affected zones (corners and surfaces between gear teeth), and stress concentration zones (assembly holes) are identified. Once these mechanically weak zones are identified, geometric optimization is applied to reinforce damaged zones and reduce stress concentration (gear geometric reconstruction -Version 3 as shown in
Figure **8**).

It is important to remind that the purpose of this reverse engineering process is to recover the functional shape of the part and to optimize its geometry in order to meet assembly, operational, and conditional limits. To this end, the last geometric improvement is performed in Step6, not only to reconstruct the gear shape compensating for its geometric deterioration due to wearing and defects during operation but also to properly fit in its assembly. In this regard, the geometry of the reconstructed CAD model after optimization needs to closely follow the overall shape of the initial worn gear. This is performed by iteratively verifying the optimized CAD model with respect to its reference scan data (scan of the worn gear) based on CAI tools. Using comparisons between the reconstructed CAD model and scan data, deviations in features of the CAD model can be identified and modified. In this step, PolyWorks^{TM} software (inspector module) is used to compare CAD and scan data in a common inspection coordinate system. Using at least three corresponding points on each set of data the CAD model and scan data are pre-aligned. They are then aligned by applying a best-fit alignment based on minimizing Hausdorff distance [4] with the Iterative Closest Point (ICP) algorithm [28]. The alignment process is presented in Figure 6.a and b wherein CAD and scan models are aligned in a common inspection coordinate system.



(a)



(b)

Figure 6: Alignment of CAD and scan models a) CAD and scan model before alignment in the common coordinate system b) Models after alignment with the Iterative Closest Point (ICP) algorithm.

This alignment of CAD and scan models allows a virtual geometric comparison between surfaces of the CAD and scan models. This measurement, as depicted in Figure 7, represents a geometric deviation of the reconstructed CAD model with respect to scan data. This deviation is mainly due to defects of the worn gear, surface wearing and thickness loss as well as to geometric modifications brought into the reconstructed CAD model during gear geometric optimization steps (step3, step4, and step5 in
Figure **8**). At the end of the process, geometric improvements on the reconstructed CAD model (gear geometric reconstruction-Version 4 in
Figure 8) specifically minimize geometric deviations between the optimized CAD model and scan data, on characteristic profiles and assembly features of the spur gear, such as bottomland, flank, and face profile, tooth fillet radius, and assembly hole fillet radii. Referring to
Figure **8**, it can be observed that absolute deviations on the characteristic profiles of spur gear reduce from 4 mm to 0.5 mm. It is worth mentioning that the 0.5 mm deviation increase in some zones is applied to compensate for gear surface wearing, which is observed during the visual inspection and assembly analysis. Geometric deviations are also verified in cross-sections of the reconstructed CAD model to ensure uniform conformance between CAD and scan models of the spur gear.

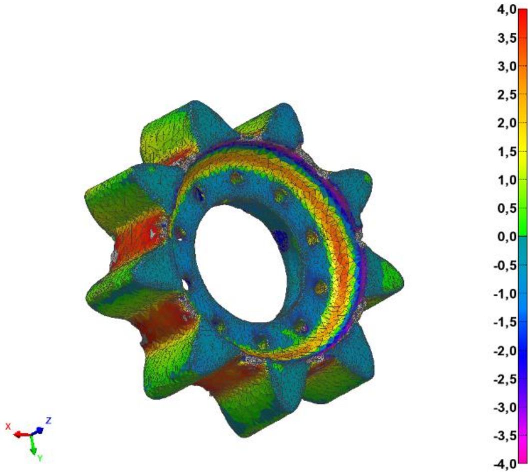


Figure 7: Virtual measurement results based on a geometric comparison between the CAD and scanned models [mm].

The final steps (Step7 and Step8) of the reverse engineering process presented in this paper aim at remanufacturing the part from recovered geometry. In our case, the part presented serious geometric damage and plastic aging weakened the material and mechanical properties of the spur gear. In this regard, the fabrication of new plastic gears based on recovered and optimized geometry is considered. The choice of material used for manufacturing these new plastic gears is based on mechanical strength (tensile tests) and chemical composition tests. Considering these tests and the fact that plastic aging affected the strength of part, a proper equivalent material is determined as a mouldable thermosetting polymer, namely polyurethane (PU). In fact, manufacturing polymer gears is less costly if compared to using other materials. Polymer gears also present various operational advantages, such as operating without a need for external lubrication, lower friction, wear, and noise which makes them well-received as elements for motion and power transmission in industrial machines [20]. The wide application of polyurethanes in industrial sectors can vary from rigid and resilient foams to durable elastomeric wheels and gears. In our case, polyurethane is used as a polymer consisting of liquid isocyanate and resin blended and gravity-casted in a mold shaped based on the CAD geometry recovered through the approach proposed. After pouring the resin blend into the mold, curing takes approximately one hour. It is worth mentioning that the polyurethane curing process is exothermic, and that casting temperature can raise to 50 ºC during this process. This point draws attention to the importance of the polyurethane molding process. at first, considering the dimensions of our part, we use two thick plates (approximately 60 mm) made of polytetrafluoroethylene (PTFE), which is well-known as Teflon™ in the industry. The mold of this part is then machined using a computer-aided milling machine and Mastercam™ software. Even though the CAD profile of the spur gear is already recovered through the previous steps, CNC programming and quality control of milling are time-consuming. As shown in Figure 9, the final geometric quality of the plastic cast gear significantly depends on the choice of tool, wearing condition, and vibration along the milling process. Meanwhile, each half of the mold is separately fabricated by a milling machine on Teflon™ plates which requires a tedious geometrical verification concerning the alignment of features during the mold assembly and fitting. In order to automatize mold fabrication and reduce fabrication delays while keeping up with the required geometric and surface texture quality of the gear, additive manufacturing based on plastic 3D printing is applied. Using additive manufacturing, both haves of the mold are 3D printed simultaneously which ensures the fitting and alignment of mold halves during mold assembly. To this end, a 3D Systems™ printer, ProJet MJP 2500™ (Figure 10), is applied to fabricate a mold in two sections.

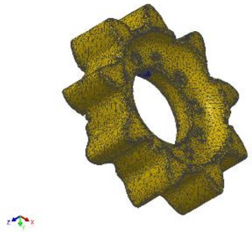
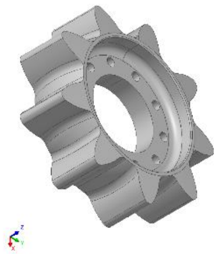
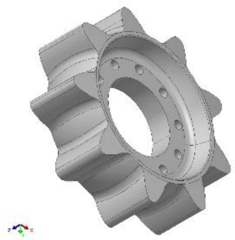
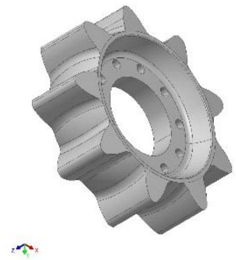
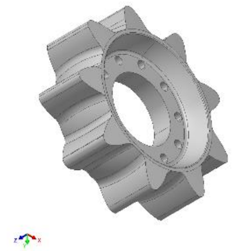
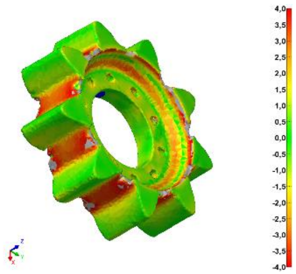
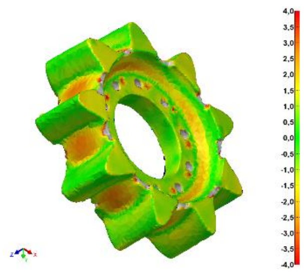
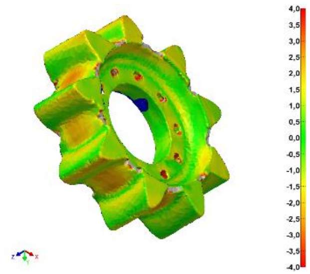
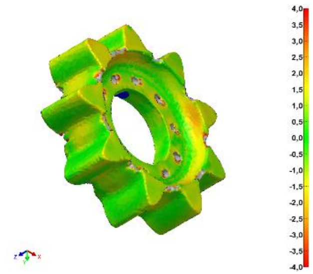
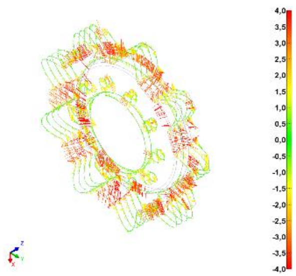
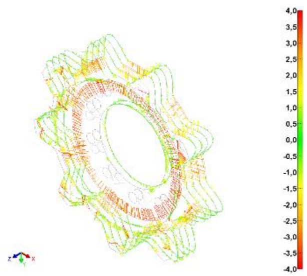
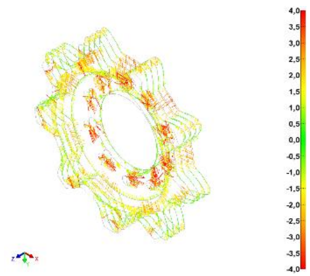
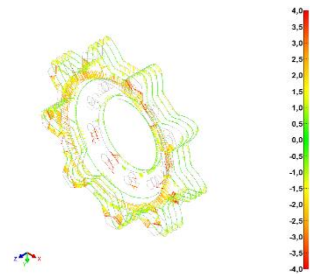
Scanned part				
	Version 1	Version 2	Version 3	Version 4
Gear geometric reconstruction and optimization (CAD model)				
Reconstructed CAD model vs scanned data geometric comparison contour map				
Reconstructed CAD model vs scanned data cross-section geometric comparison				

Figure 8: Geometric optimization of the reverse-engineered CAD model with respect to the scanned part [mm].

In this way, the recovered geometric shape of the gear is virtually carved into the mold material and the featured mold model is divided into layers preparing the profile of each 3D printing layer. Finally, by printing each layer and stacking them up, each section of the mold is fabricated in almost eight hours. The postprocessing in hot steam and hot oil surface cleaning provides a very smooth surface with good geometric quality.

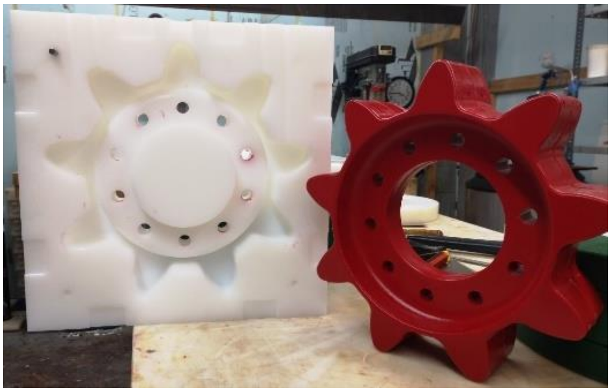


Figure 9: The machined mold made of Teflon™ and the final product based on gravity casting of polyurethane.

(a) (b)

Figure 10: Mold fabrication using additive manufacturing a) ProJet MJP 2500™ b) Postprocessing and cleaning accessories used.

4 CONCLUSION

In the present work, an automated remanufacturing process of worn mechanical parts via point cloud surface acquisition is developed as a step toward smart maintenance. A 3D laser scanner is used to acquire the shapes of a worn gear, from which a CAD model is recovered and optimized to remanufacture the part. Indeed, many industrial sectors are experiencing long delays in spare parts supply, which dramatically affects production and increases downtime periods. An automated and flexible remanufacturing of a damaged spur gear made of plastic material, based on reverse-engineering methods is performed. In the end, the remanufactured gear is successfully installed in its assembly inside mining equipment and performs in its best condition. Virtual measuring of freeform surfaces, geometric recovering and optimization of the part, additive manufacturing of molds, and gravity molding are used to remanufacture this part in a shorter time and at a lower cost. This research mixes experimental and numerical work, using computer-aided inspection (CAI)

approaches. CAI allows verifying geometric deviations on surfaces as well as in cross-sections of the optimized CAD model obtained to ensure uniform conformance between the reconstructed CAD model and scan data of the existing spur gear. It is remarked that by using this new approach, absolute deviations on characteristic profiles of the spur gear reduce from 4 mm to 0.5 mm, which respects geometric standards and assembly constraints of the part. In this regard, optimization of the CAD model includes a geometric reinforcement of the part under static and cyclic charges. In this case, downtime decreases from an estimated six months to three weeks. This approach also contributes to improving asset management and encourages local manufacturing companies.
Although the results of this research are promising, future work should lead to significant improvements. The validation of our models on a larger range of parameter variation and multi-objective optimization can be considered for future studies. In this context, the performance of the proposed method can be verified on more complex parts and parts made with various materials such as metallic and composite materials. It should also be applied to parts in various industrial sectors (aside from mining) to validate the uptime improvement in other contexts. The method could also be improved by adding machine learning (ML) algorithms to detect geometric defects and wear on the scan model.

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