



Design for automated inspection in remanufacturing: A discrete event simulation for process improvement

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ABSTRACT

Remanufacturing is a process of restoring end-of-life (Eol) products to “as new” condition with a matching warranty. It offers significant economic benefits to remanufacturers as well as providing enormous environmental and social benefits. However, achieving remanufacturing is complex and uncertain due to varying product return quantity and quality. These uncertainties call for proper assessment of returned Eol products to extract the most value from them. The evaluation involves inspecting the Eol products on arrival for remanufacturing, thereby making the most appropriate Eol decisions. These decisions are made by expert personnel by visually assess these products manually or using semi-automated techniques. However, the accuracy of these decisions is subjective, time-consuming, and prone to missing defects. The need to develop processes and tools for efficient, reliable, and repeatable inspection in remanufacturing becomes inevitable. Automated inspection becomes handy to improve the assessment of these defects as well as saving time. This paper proposes design-for-inspection as a tool to enhance remanufacturing. A discrete event simulation of this model for the torque converter remanufacturing process is presented and highlights the benefits of automating the remanufacturing inspection process. It further suggests the design improvements to obtain an enhanced automated inspection.

1. Introduction

Remanufacturing is a sustainability-conscious approach to maximising existing products, thereby considering future generations through our daily behaviour. Remanufacturing is driven mainly by the economic and environmental benefits achieved through the processes where cost savings on energy, materials, and emission are obtained, with the most negligible impact on the environment due to emission and lesser extraction of materials from the natural sources. However, the end-of-life (Eol) product management processes are the most challenging to manage due to the significant variations in Eol core condition as they are returned (Tolio et al., 2017). These management processes also significantly impact the environment and economy (Boudhar et al., 2017). Moreover, these processes have witnessed limited research, unlike the manufacturing sector, which is less complicated.

Besides, to maximise and harness potentials in these Eol products, the right approach would be to develop designs, strategies, and technologies that would at least last longer, thereby sustaining multiple life cycles through different end-of-life strategies while performing at optimal levels. Perhaps, most of these products will not perform at

optimal levels at the end of their first life cycle, thereby constituting another challenge of maintaining them. The products that have failed or prone to failure pass through some form of supply chain activities and remanufacturing, where the Eol products are collected, assessed, recovered and restored to as-new conditions with warranty through remanufacturing. This process of restoration is known as remanufacture in most literature.

Besides, to remanufacture these Eol products, the products are gathered and returned as cores, where the remanufacturing process begins. After these returns, new challenges arise as the returned product information is usually unknown because there are predominantly no data about the product use conditions and its current state. To further explore the remaining useful life of these Eol products, inspection is crucial as the product's current state is assessed to determine the appropriate end-of-life strategy to adopt and if there is a need to proceed to remanufacture (Fegade et al., 2015). Nevertheless, researchers further outlined that the processes of assessment, grading, and sorting of these products are labour and time intensive (Errington and Childe, 2013), thereby suggesting the need for technologies to automate these processes.

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This research investigates the inspection process in remanufacturing as a holistic activity, which involves performing quality control before, during, and after remanufacture. Inspection in remanufacturing is a continuous process that starts from the arrival of the cores and continues until the products are ready to return to the market. This process is predominantly a manual process because the level of details needed at every inspection point differs and solely depends on the expert's experience performing the inspection. Researchers have also outlined that remanufacturing process automation is low (Kurilova-Palisaitiene et al., 2018).

We explore this gap by proposing an automation approach for inspection in remanufacturing tagged design for automated inspection (DfAI). This approach will help practitioners, academics, and researchers, correctly understand the requirements for achieving automated inspection in remanufacturing.

1.1. Remanufacturing

Remanufacturing is a process of returning Eol products to as-new conditions with a matching warranty. It involves seven key stages: identification, disassembly, inspection, cleaning, reconditioning, reassembly, and testing. The respective steps involve unique activities that differentiate them from each other; however, some of these processes are repetitive in a single Eol product's remanufacture. Among the techniques includes the identification stage, where products are identified before disassembly. The other processes include the inspection and cleaning steps where the products are cleaned before reconditioning and cleaned again before packaging for delivery to another customer. Perhaps, the inspection process is performed before the identification, disassembly, cleaning, and testing stages.

The most vital benefits of remanufacturing include that high-quality products are provided at a cheaper cost and saving energy while lowering CO₂ emission to the environment. However, each of the respective stages of remanufacturing offers significant challenges. Researchers have considered these challenges independently to effectively address the problems encountered during remanufacturing, with corresponding design approaches proposed to manage them. A holistic approach termed design for X, where X represents remanufacture. It provides a method that facilitates optimal decision making to improve remanufacturing while considering economic and environmental benefits (Fegade et al., 2015). Various designs, procedures, and tools have been proposed and investigated extensively for remanufacturing (Fegade et al., 2015) and reviewed (Hatcher et al., 2011). However, apart from the design for remanufacturing, other design approaches have been proposed to enhance remanufacturing, including the design for testing (Tant et al., 2019), testability (Mosch et al., 2016), design for disassembly, design for multiple life cycles, design for evaluation, design for upgrade, eco-design, design for core collection, (Charter et al., 2008). Of these designs, only the design for evaluation concerns the inspection process in remanufacturing, of which it models inspection in remanufacturing as a manual process.

However, inspection in remanufacturing has been an active research area and to automate the inspection process, we propose the DfAI system. The DfAI aligns with the principles of design for remanufacturing, highlighting that product design is essential to the operation of the product remanufacture (Tant et al., 2019). The main driver of inspection is to extract the most value from Eol products and assist industrialist, experts, and academics in making a significant decision with the Eol products at the earliest stage of the remanufacturing process. The inspection ensures that products whose tolerances fall short are removed as soon as possible while reducing the need to process these Eol products further, thereby saving time, cost, energy, and materials such as cleaning chemicals and fluids.

Perhaps, to achieve this research aims, the remaining parts of the paper are structured as follows. Section 2 provides a brief introduction to inspection and the approaches to inspection in remanufacturing.

Section 3 presents the design approach for automated inspection and the numerous benefits. Section 4 shows the conceptual framework for the design for automated inspection. Section 5 details the proposed design simulation and the case study of the torque converter remanufacturing inspection. Section 6 discusses the implications for remanufacturing practitioners adopting the proposed approach. Section 7 finally provides the conclusion and research limitations.

2. Inspection

Inspection is the careful search for non-conformities in a given test case. It is a crucial part of any remanufacturing processing stage, used to maximise Eol product recovery. Product assessment is inspired by the need to meet quality requirements because of customer awareness of the quality specification and strict policies on products returning to the market after reaching the first end-of-life (Eol). Inspection has witnessed limited research compared to disassembly and other remanufacturing stages; however, the ease of achieving other parts of the remanufacturing process, especially disassembly, somewhat improves assessment. Therefore, one of the most important considerations for the design for life-cycle is the ability to disassemble a product at Eol. However, the disassembly contributes to effective inspection; it enhances a proper assessment of products and a given product's components. An efficient inspection will provide significant savings in resources, enhanced quality of products returned, the value extracted from the Eol processes, and reduces waste from remanufacturing sent to landfill.

Further, an overview of the inspection processes and schematics for remanufacturing is presented (Errington and Childe, 2013). The performance of inspection systems is evaluated using key performance indicators, including flexibility, quality, time, productivity and delivery reliability (Butzer et al., 2017). Effective information management is vital for remanufacturing inspection, with different researchers evaluating the value of information management for inspection to address remanufacturing uncertainty (Gildea and Adickes, 1993; Kulkarni et al., 2007). They showed that relevant core inspection information could be processed using radio frequency identity (RFID) tags and could be helpful to assess product conditions at end-of-life.

However, the remanufacturing inspection research has been slow; most often, the inspection process is integrated into functional remanufacturing shop floor (Aksoy and Gupta, 2005), thereby facilitating core classification and quality. Furthermore, researchers have approached the inspection process in remanufacturing using different techniques, including; the use of the Taguchi system and other quantitative methods (Ridley and Ijomah, 2015; Yazid et al., 2015; Abu et al., 2016; Ridley et al., 2019), and learning models (Gibbons et al., 2018; Nwankpa et al., 2019). Besides, the metal magnetic memory techniques for predicting the residual useful life of cores for remanufacturing have also been surveyed extensively (Zhang et al., 2011). Similarly, the pre-disassembly inspection approach using the analytic and hierarchical process (AHP) has also been explored to determine the remanufacturability of machine tools, with the authors investigating methods of evaluating remanufacturability. These include technology feasibility, which considers all remanufacturing processes (Du et al., 2012). Perhaps, this latter approach to inspection cannot be applied after the pre-disassembly stage, making it unsuitable for automated inspection.

Nevertheless, from the inspection techniques found in the literature, a significant trend is that majority of the methods identified similar faults, either surface faults or subsurface faults, thereby making the real-time automation of inspection in remanufacturing unattainable. To achieve this automation, the design for automated inspection is the focus of this research.

Remanufacturing inspection is categorised into two levels based on the location of the defect on an end-of-life product. The surface defects represent defects identifiable on the external parts of a given product. In contrast, the sub-surface defects require non-destructive inspection techniques to identify the flaws within the end-of-life product. Surface

inspection is also visually assessed, while the sub-surface assessment is performed using non-destruction inspection techniques (Tant et al., 2019). Conversely, to achieve real-time automated inspection, the inspection system must have the capacity to identify both the surface defects on a component as well as the sub-surface defects. This approach ensures that products returned have reasonable quality assurance and can perform optimally like the new parts before the warranty is placed on the Eol product, to guarantee that the performance is 'like new' products.

Conversely, there are three types of inspection performed in almost every remanufacturing service facility. They include manual, automated, and semi-automated inspection techniques. Human experts perform manual inspection and offer adequate accuracy levels in the low paced industry. The automated inspection has no human interference but sensor systems, while the semi-automated inspection has some inspection activities automated (Kopardekar et al., 1993). However, manual assessment has significant limitations, including that it is time-consuming and most susceptible to missing defects (Cemenska et al., 2017). It usually adopts visual inspection, in which a product, material, or component is examined for deviations from ideal conditions using the eye or lights. This inspection's quality depends on the quality of the sensing device and the lighting conditions (Gopinath et al., 2011).

2.1. Core inspection approaches in remanufacturing

Core inspection is an essential part of reverse logistics. Reverse logistics is a systematic process of managing product returns to extract the maximum value from them (El Hachimi, Oubrich and Souissi, 2018). It is one of the challenging stages in remanufacturing and directly affects inspection types due to cores' critical and uncertain conditions as they arrive. Researchers have categorised remanufacturing core inspection into three groups according to the source of core acquisition in literature. This categorisation includes core dealers, independent service centres, and internal service centres (Tolio et al., 2017). The core dealers approach to inspection requires that remanufacturers know the conditions of the cores they receive from the dealers and, with the cores' cost, depending on their state. Besides, the independent service centres approach is an inspection performed before the point of collection. This assessment is achieved using terms of the Eol return policy, in which the customer agrees that the Eol product is not damaged or defective.

A typical example is the Xerox Green World Alliance Program. Customers are issued with labels to return Eol toners for recycling. There are imposed charges on customers who return products that do not fall into the stated conditions and categories for recycling (Xerox Europe, 2020). Finally, the internal service centre approach is a type of inspection performed at the site for remanufacturing where returned and identified Eol products are classified into remanufacturable, repairable, or scrap. Typical examples of on-site inspection are found in these remanufacturing cases for crankshafts (Abu et al., 2016) and caterpillar engines (Ridley et al., 2019). However, researchers further classified the internal service centre inspection to involve three stages of examination, including core acceptance, where cores are inspected on arrival. The part inspection involves inspections performed during the reconditioning and final product testing stages, where products are inspected before certifying the quality (Errington and Childe, 2013). These validate that inspection during remanufacturing occurs at different locations and the form of assessment required differs depending on the stage. The internal service centre based inspection is the most used inspection technique in remanufacturing, especially for the third-party remanufacturers (see Fig. 1).

2.2. Challenges to remanufacturing inspection

Numerous authors have explored the challenges to remanufacturing (Lage Junior and Godinho Filho, 2016; Kurilova-Palisaitiene et al., 2018). They outlined that uncertainty in material recovery, among other

difficulties, represents a significant challenge in remanufacturing. Besides, to determine the levels of material recovery, appropriate inspection is vital, as it guides the decision of what to recover. This inspection is mainly applicable to internal service centres, where a process-based inspection is performed at the different stages of remanufacturing, as shown in Fig. 3. However, a significant challenge for this existing inspection techniques in remanufacturing outlined by researchers is that it lacks automation (Siddiqi et al., 2019) and tools and expertise to achieve non-destructive inspection (Tant et al., 2019). To address some of these automation challenges, the design for automated inspection (DfAI) is proposed. This DfAI finds application in automating the inspection processes during remanufacturing when adapted (see Fig. 4) (see Fig. 5) (see Fig. 2).

For managers, the DfAI provides a systematic approach to quickly outline the requirements to set up an automated inspection system, thereby streamlining the process to specific tasks and outline the sequence of managing the inventory storage through a computerised process, enhancing the shop floor activities.

3. Design for automated inspection (DfAI)

The design for automated inspection is a process automation approach for remanufacturing that considers both surface and sub-surface defects. The system can identify the product's condition and make the economic decision about the end-of-life strategy for the design. Making the right decision at the earliest stage saves numerous resources, including time, chemicals for cleaning, resources for disassembly, energy, and many other benefits.

Inspection in remanufacturing has remained an active research area in the literature; however, the existing research on remanufacturing inspection has not fully explored the design for automated inspection. This design for automated inspection represents an extension of the design for testing and design for evaluation. The design for evaluation describes a manual inspection technique that depends mainly on the inspector's knowledge in identifying and defining the desired quality standard for a product or component (Charter et al., 2008). In contrast, the design for testing provides a quantitative assessment of components during remanufacturing, which (Tant et al., 2019) outlined that it offers higher structural integrity. The DfAI incorporates an automated visual inspection model that would provide the surface inspection of Eol products (Gibbons et al., 2018; Nwankpa et al., 2019), and the design for testing, which offers sub-surface testing and inspection of Eol products using non-destructive inspection (NDT) techniques (Mosch et al., 2016).

The automated visual inspection is an image processing approach of quality control and industrial inspection. The visual inspection techniques involve different techniques of modifying the captured images of an object to make a reasonable decision from the photos. The approaches involve filtering, projection, learning, hybrid, and other algorithm-based automated visual inspection systems (Huang and Pan, 2015). The visual inspection considers only the surface defects on the products or parts inspected.

The design for testing proposed for sub-surface testing provides a technique to use ultrasonic sensors in single-sided inspection to assess Eol product while measuring the ultrasonic signals' coverage on the object to determine the conditions. The authors outlined the single side domain inspection as the similar inspection approaches used in the industry and supported the industry's real applicability (Tant et al., 2019). The design for testing framework involves assessing internal wear and tear on the product's components using ultrasonic NDT and inspection techniques. This approach is a quantitative technique for assessing structural integrity for components before and during remanufacturing.

3.1. Benefits of design for automated inspection

Inspection is an essential part of the remanufacturing process because it determines the extent of value recovery and the size of

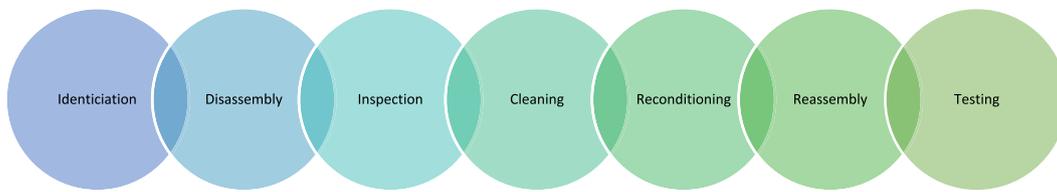


Fig. 1. Pictorial view of a typical remanufacturing process.

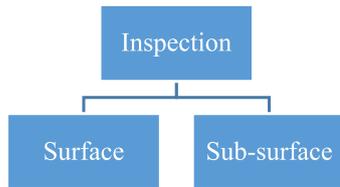


Fig. 2. Levels of inspection In Remanufacturing.

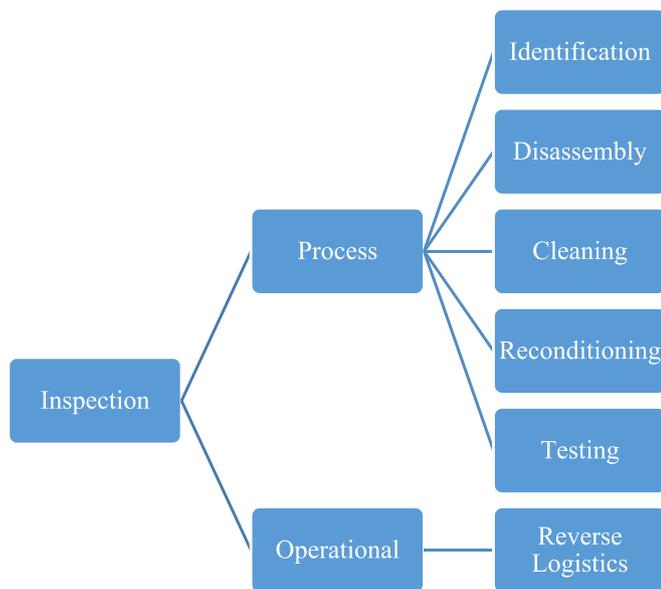


Fig. 3. Stages of Inspection In remanufacturing.

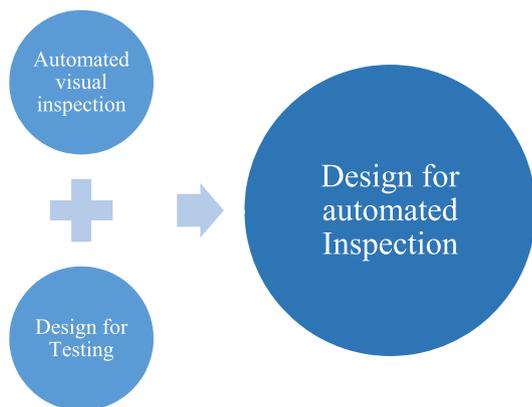


Fig. 4. Approach to achieve design for inspection in remanufacturing.

alongside the efficient use of material and reductions in non-remanufacturable parts, improved value recovery and quality assurance of remanufactured products and a reduction in remanufacturing cost (Siddiqi et al., 2019). Other benefits of adopting automation across the remanufacturing process include enhanced throughput of the overall process, improved accuracy in product and personnel safety, reduced workplace risks and hazards associated with the remanufacturing process and reduced factory lead times. These benefits provided by the DfAI approach also improves the overall remanufacturing process.

4. Conceptual approach for design for automated inspection

The conceptual design for automated inspection implementation involves the use of vision sensor systems, usually a camera. A group of ultrasonic NDT sensors, IoT sensor data that captures the middle-of-life data about the product for inspection forms part of the inputs. Also, a collector tray, some conveyor systems, and some analytical models to process the visual and ultrasonic data. However, in the current practice, the middle-of-life data is not always available during remanufacturing; therefore, the DfAI system implementation and decision-making will primarily use the vision and NDT sensor data to achieve the automated inspection.

4.1. Automated visual inspection (camera data)

The visual inspection stage is a critical stage during the inspection. It helps to assess systems’ structural integrity, products or components to identify defects (Oyekola et al., 2019). The visual data obtained by using the camera connected to capture the specific objects for inspection. The camera records the components and the recorded samples used to train the deep learning classifier. The model design involves six key stages: data capture, pre-processing, model selection, training, evaluation and improvement (LeCun et al., 2015; Jiao et al., 2020; Nwankpa et al., 2020).

The data capture stage is the most crucial in the model development plan because it is the stage where essential model development considerations are made. The types of visual inspection faults anticipated by the model are pre-determined at the model design stage. The types of defects expected are identified and recorded, labelled and used as training samples. The pre-processing step involves resizing the recorded images to suit the deep CNN model architectural requirements as well as creating the models training, validation and test sets, obtained as a percentage of the available data and used for training the model.

The model itself is a computational algorithm consisting of multi-layer convolutional neural networks (CNN). These layers include the convolutional, pooling, activation, padding, batch-normalisation and regularisation layers. The model selection consists of creating a deep convolutional neural network model or choosing a high performing model for transfer learning on the new data. The training step involves passing the training and validation data over the model over some specified number of times, learning the model’s features, and monitoring the model predictions’ accuracy. These models learn the data patterns during training and validation. The training process involves automatically choosing the samples’ specific features to represent the image data patterns. The CNN’s uses the convolutional and pooling layers to learn the data patterns from small localised regions called

reconditioning required to return the product to “as new condition” with a matching warranty. The automation of remanufacturing reduces the complication in the process as suggested by different researchers,

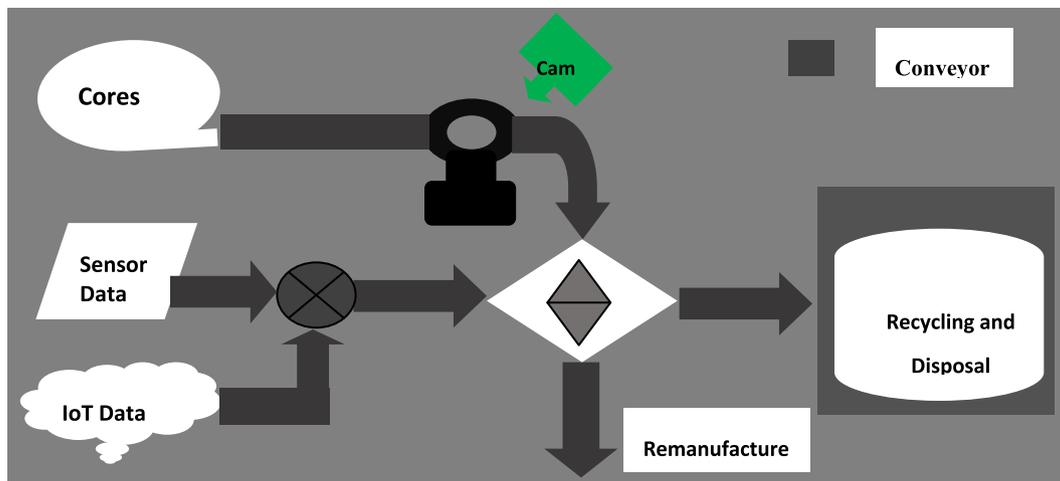


Fig. 5. Conceptual model for Implementing Design for Automated Inspection System.

receptive fields. The first layers learn from raw image pixels to motifs by detecting irregular edges to parts of objects, which are combined to reproduce the items with underlying features (LeCun et al., 2015). After the training and evaluation, the obtained model parameters, often referred to as weights, are saved and used to infer on newly recorded samples that were not part of the training samples. The model evaluation step consists of passing the test set on the model to determine its ability to generalise on unseen data. The inference is performed by connecting a camera design, focusing on a conveyor, carrying the returned end-of-life products ready for remanufacturing or the post disassembly inspection where surfaces are automatically inspected for faults using the model and the connected camera focusing on the products or components. This approach to visual inspection model was demonstrated by (Nwankpa et al., 2020) for seven different visible faults types, including identifying pitting, rusting, crack, and other combination faults recorded, pre-processed and used to train a deep learning model for remanufacturing inspection.

The surface faults here refer to surface defects or smoothness, giving a clear idea of a suspected defect on the component or product, much like visual inspection experts would outline before or during remanufacturing. This type of inspection has found the most significant medical image analysis application, especially to analyse scan images. A literature review of the use of deep convolution neural networks in medical image analysis is available here (Litjens et al., 2017). Some researchers have investigated the application of machine learning and deep learning for remanufacturing inspection using computer vision techniques. These papers provide detailed procedures to achieve an automated visual inspection for remanufacturing (Gibbons et al., 2018; Schlüter et al., 2018; Nwankpa et al., 2020).

Conversely, the design for automated inspection uses a photogrammetry approach that outlines optimal camera placement for adequate coverage of an object captured using triangulation of multiple cameras (Olague and Mohr, 2002). The DfAI system proposes to achieve this object coverage using a single camera view and data augmentation techniques. This technique involves using a fixed camera to capture different object orientations and using image processing techniques to achieve other object transformations, including scaling, rotations, flips, height and width shifts, etc. (Taylor and Nitschke, 2017). These transformations enhance the model generalisation in practice and achieve similar multi-camera recording results.

4.2. Non-destruction inspection (sensor data)

The non-destruction inspection stage is another crucial stage to determine the structural integrity of the product's components. During

remanufacturing, a key consideration is for the parts of the product for reuse lasting another life-cycle without failure, thus calling for the structural integrity test of the components before reuse. The design for testing acts as proof of the mathematical framework for achieving NDT inspection as a remanufacturing design consideration. By adopting this design approach and adjusting the components shape and data acquisition geometry, the design-for-testing technique provides the advantage of enhancing in-service inspection and increasing the range of products suitable for remanufacturing (Tant et al., 2019).

The sub-surface inspection involves adopting the design-for-testing approach where a multi-objective optimisation focuses on maximising the coverage of ultrasonic fields throughout a component while minimising the number of ultrasonic transducers used to achieve sub-surface component assessment. Researchers investigated the practical implementation of the design-for-testing to understand the optimal placement of ultrasonic sensor sources on the component boundary and the ultrasonic field coverage area using PZFlex software (Tant et al., 2019). This design for testing step confirms the design consideration of the products or components shape during design. It enhances non-destructive testing, thereby aiding their integrity and certifying quality.

4.3. Internet of things (IoT data)

The technology of internet-connected devices, often referred to as the internet of things (IoT), is an essential technology of the future for remanufacturing that provides connectivity and interaction between physical devices and the cyber world. Recent advancements in software, hardware and communication technologies have enhanced the emergence of IoT connected sensory devices to provide data measurements and observation from the physical world (Mahdaviinejad et al., 2018). This approach uses more recent designs where embedded chips record data about product health during use and decide product conditions at end-of-life. The IoT data includes the middle-of-life data incorporated in the pre-disassembly inspection during remanufacturing where available. This data is only available to original equipment manufacturers that remanufacture their products at end-of-life and alongside other remanufacturing decision-making.

Conversely, the IoT data is usually not available to third-party remanufacturers for most products that are remanufactured. Perhaps, where this data is publicly available, it would be helpful to enhance automated inspection system design for remanufacturing application.

5. Simulation implementation for the design for inspection

Simulation is an essential method of analysing process problems with

vital details of assumptions about the process. It is an approximate imitation of a system that represents the operation over a specified time. Process simulation enables performance optimisation, thereby enhancing the productivity of the system under consideration. For a typical case like remanufacturing, the formal process is modelled and transformed using blocks diagrams, with the performance evaluated during tuning.

The design for automated inspection system simulation uses a discrete event simulation approach, modelled using Arena software. Arena is a discrete event software simulation tool that uses blocks and templates for representing models (Guner and Seker, 2008). Arena uses simulation language (SIMAN) to model processes (Sturrock and Pegden, 1990). It has different modules for representing processes and objects, including the “create module” for input creation. The “assign module” is also helpful for parameter definition and the “process module” for specific inputs aggregation. The “station module” highlights parameter flow, while the “route module” is used for sequencing. The “decision module” to specify desired model conditions, as well as the “resources module” to display simulation outcomes, and finally the “dispose module” to release simulation resource.

This simulation is informed by remanufacturing researchers (Butzer et al., 2017), who outlined that there exists a limited knowledge-based assessment of remanufacturing processes through simulation to assess and improve remanufacturing. The model approach adopted was suggested by (Sturrock and Pegden, 1990), who highlighted that large manufacturing systems are better modelled by decomposing them into functional groups, modelling the smaller functions without any logical order before combining the overall design. The remanufacturing process can also be modelled independently, especially for the inspection process without any specified order.

5.1. Torque converter system remanufacturing

The torque converter (TC) system is a particular part of an automatic transmission system, used to couple power to the transmission system using fluids, thereby preventing the engine from stalling. It consists of components that include the stator, impeller, turbine, blades, housing, lock-up clutch, and shaft. The automated inspection of these high-value parts of TC evaluated using the proposed design for automated inspection. This simulation provides a deeper understanding of the requirements for the DfAI systems. A gallery of some of the simulated high-value components of the torque converter unit for remanufacturing is depicted, with a remanufactured TC shown in the top-left image of Fig. 6.

The modelling and simulation involve two sections where the

analysis of the independent inspection levels consider the surface and subsurface inspections, respectively. As Mackie Transmission is a third party remanufacturer and there was no available middle-of-life data, the model evaluates surface and subsurface faults alone. The surface inspection can be helpful for core arrival inspection, where cores are inspected and taken into acceptance for remanufacturing and afterwards stored until when needed. However, if the components fail, other Eol approaches are called by the system.

The visual sensor systems for surface inspection will incorporate at least three cameras placed 120° apart as suggested for optimal camera placement or a single camera fixed at some distance above the collection tray. The camera will capture an image after 120° rotation of the collector tray, covering the object’s entire surface view during an inspection. However, the greater the number of views, the better but the trade-off with the inspection speed comes into consideration.

The simulation inputs being discrete values consist of seven respective true and false samples of the stator, impeller, turbine, blades, housing, lock-up clutch, and shaft of the torque converter system. The model definition has fourteen components as the inputs to the system, with the seven true samples of these parts modelled as suitable for remanufacturing. In contrast, the remaining seven false pieces sported as non-remanufacturable. These parts were modelled using numeric representations and coded into a decision block. The inspected surfaces are sorted and conveyed to a specific collector named with part numbers in Fig. 7. The sorting of the process is performed with eight actuators, with each remanufacturable part sorted and stored or sent to the second stage of inspection. Besides, for the non-remanufacturable components, the decision block routes the element through the “failed” process block and sent to the disposal station for recycling and disposal before the system resource is released back through the dispose block.

The evaluation of this automated inspection of the seven TC high-value components with discrete event simulation of the parts’ movement from the collection point to storage modelled as a time delay between the collection points to the “storage” with the other process remanufacturing not considered. The “create” block provides the model inputs, and it moves in no specific order, as shown in the blocks. The “assign block” specifies the attributes for the model’s parts, labelled numerically. A process block combines the part arrival process named “Process 1” while the method performs the final inspection before deciding if to remanufacture or choose other Eol options. Smooth visual animation of the objects’ movement verifies the decisions made by the specified conditions of the modelled parts. The model incorporated a queue system for achieving real-time implementation as represented in the simulation and a seize delay release action logic, such that two components cannot collide during an inspection.

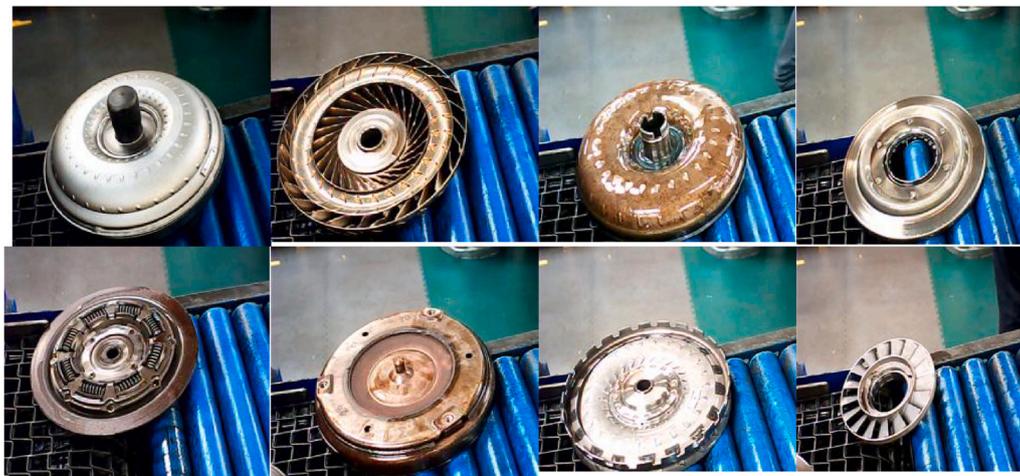


Fig. 6. Sample Torque Converter components represented in the simulation.

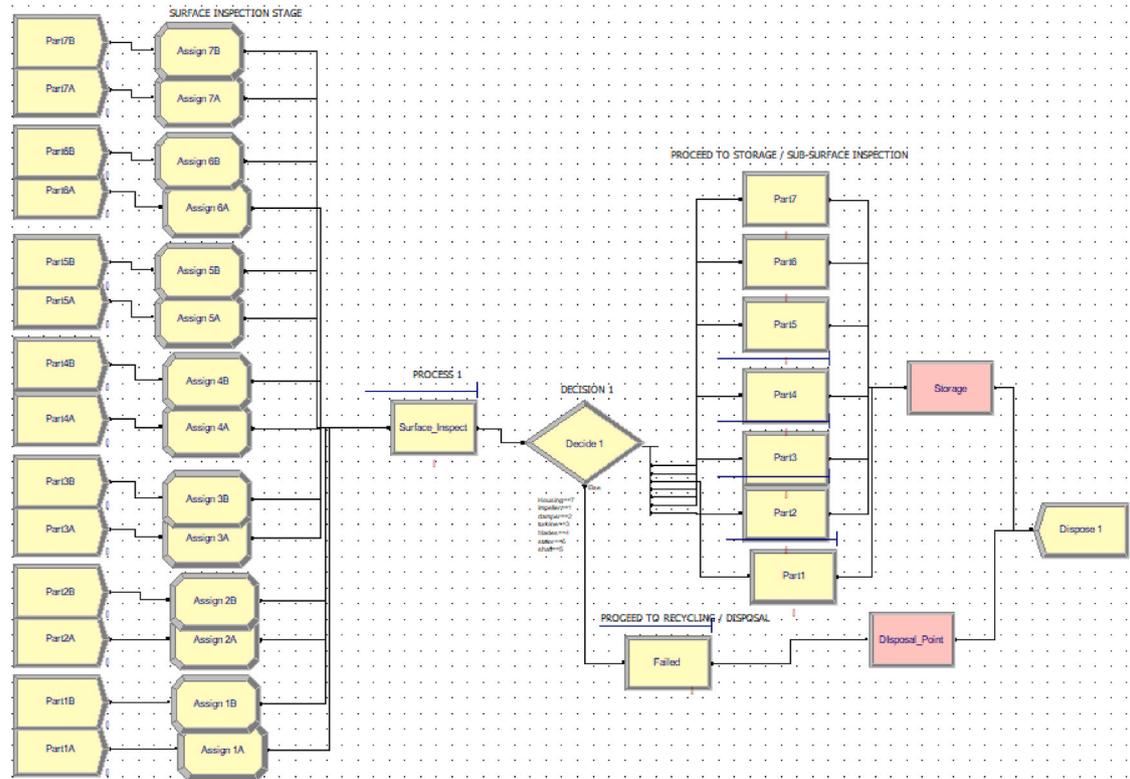


Fig. 7. Surface inspection stage.

The subsurface inspection stage is performed by the NDT ultrasonic probes/sensors connected around the collection trays. The number of sensors modelled numerically as sensor 1,2, ..., N, and are used to scan the surface on the tray to test subsurface defects in the material. Suppose a highly defected component is found through the defined decision limits. In that case, it is sent to the “disposal station” for recycling to obtain functional spare parts and system resources released by the dispose block. However, suppose the decision block accepts the conforming Eol products; they are routed to the main remanufacturing processes for disassembly, cleaning, reconditioning, reassembly, and testing before returning them to market. The subsurface inspection model simulation is shown in Fig. 8.

The other remanufacturing stages are represented with process blocks and a route that highlights the process model stages incorporated to easy process recognition. Finally, combining the two phases of inspection where visual inspection and the NDT inspection are fused, a hybrid inspection design named DfAI is obtained. This design technique can automate inspection in remanufacturing with ease. The DfAI system

has shown promising results from the simulation. Nevertheless, the model’s in-depth statistics are not discussed in great detail because we focussed on the design considerations for achieving automated inspection alone. Dissecting the automated inspection for each remanufacturing process is our future research, with more details about the model to follow.

The sequence of the route specifies the model’s resource use. After the inspection, the path is placed in series to follow proceeding stages for the remanufacturing process using “by sequence” on the route block named “Route Parts”, thereby taking the inspection result through the subsequent steps. Different visuals show the changing process stage during the simulation and queues to represent the resource-demanding processes. A visual representation of the conveyor system’s moving parts highlights the products or components on transit and the inspected components’ final destination. Appendix A shows the overall system simulation model for more information.

This design approach simplifies the remanufacturing inspection process’s automation into two vital steps, eliminating the setup

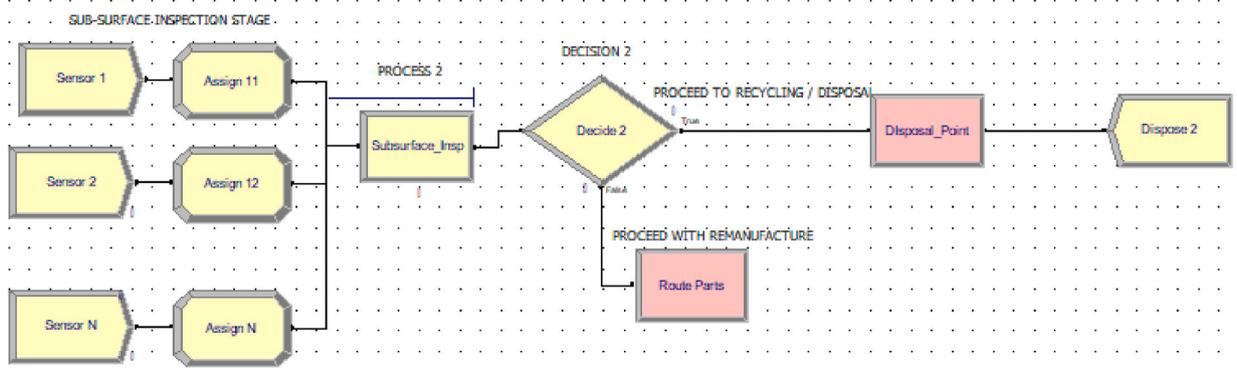


Fig. 8. Subsurface inspection approach.

complexity and improving the inspection process. It also outlines the necessary resources needed to achieve automated inspection in remanufacturing.

6. Implications for practitioners adopting design for automated inspection

This simulation model provides the necessary details for deploying an automated inspection system, among other remanufacturing benefits. It highlights the setup hardware requirements, visualisation of the overall inspection process to identify and reduce operational bottlenecks, provides an avenue to explore new methods of process improvement, as well as having the potentials to improve inventory management for the Eol products thereby enhancing operational efficiency, profitability and delivery times for the remanufactured products. These benefits are derivable if the proposed DfAI system technique is incorporated as a remanufacturing design approach, thereby aiding inspection.

The most significant advantage of the design approach is that it can be implemented on an existing remanufacturing process by re-engineering the methods and systems, thereby creating new designs for the automated inspection.

7. Conclusion

This research presents a theoretical approach to designing inspection systems for remanufacturing. It proposes the design for automated inspection as a design method for remanufacturing automation. Testing and automated visual inspection procedures are combined to achieve a hybrid automated inspection system to support automated remanufacturing inspection. An implementation approach, as well as a discrete

event simulation of the DfAI model, is presented. The simulation considers seven high-value components of the torque converter system. The DfAI system decision about the non-remanufacturable product activates the recycling/disposal Eol strategy for the product. In contrast, the conforming products are processed for storage and further remanufacturing, depending on where the DfAI system is applied on the shop floor.

The internal inspection of these products is performed using a group of NDT sensors that provide subsurface inspection for the parts. The DfAI process can be integrated before disassembly, after disassembly, cleaning, or reconditioning remanufacturing stages. The DfAI in remanufacturing will provide tremendous benefits, including consistent quality products, enhanced throughput, reduce exposure to injuries, and guarantee the integrity and reliability of components of inspected products during remanufacturing, thereby improving remanufacturing in general. The only observable limitation of the DfAI system is the ease of providing a reliable sub-surface inspection system setup for remanufacturing, which is a progressive research area to date. This challenge results from integrating numerous sensors to perform structural integrity tests on the components during remanufacturing.

Declaration of competing interest

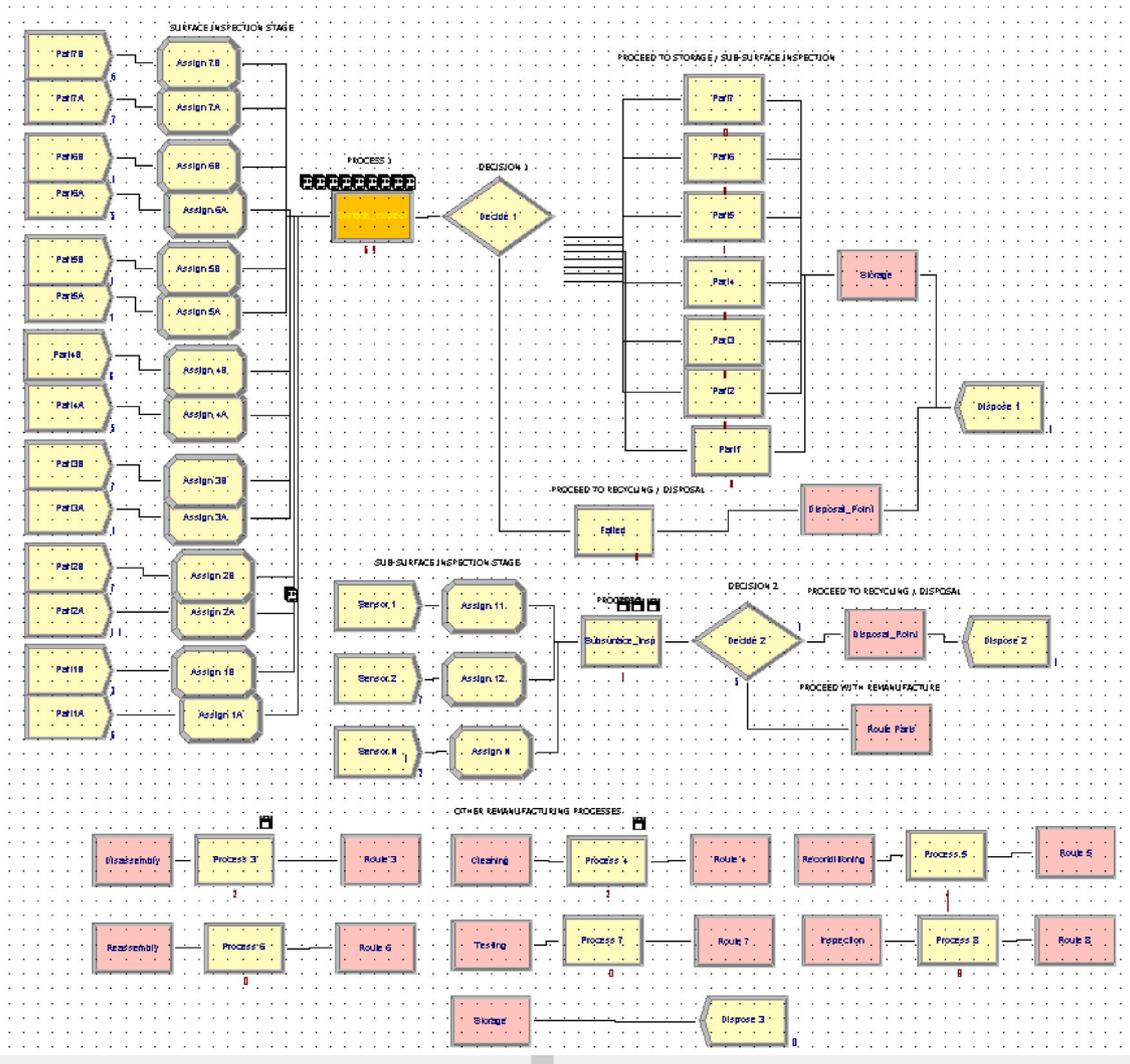
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Appendix A shows the overall simulation diagram of the DfAI design model for remanufacturing showing the different shapes of objects used in the model.



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