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3D Data Integration in the Digital Twin for Circular Economy

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Abstract

Given the scarcity of resources, manufacturers of mechatronic products must enhance their Circular Economy practices. This paper addresses the challenge of geometrical digitization and digital continuity throughout all phases of a product's Life Cycle. An approach based on Digital Twins, incorporating 3D scanning data, is proposed. The comparison with initial design data enables automated quality assessment regarding appropriate Circular Economy strategies to feed back into product design. A literature review is conducted in the field of curve, surface, and geometry reconstruction of 3D point clouds. Limitations, research gaps and potential future works with a focus on R-Strategies within Circular Economy are presented.

Keywords: Design for Circular Economy; 3D Scanning; Digital Twin; Reverse Engineering; R-Strategies; Feedback-to-X

1. Introduction

In manufacturing industries, the need to apply and improve Circular Economy (CE) practices is well understood. There are certain main driving factors: The scarcity of resources requires utilizing R-Strategies (repair a product, recover its raw materials, etc.) to keep already used and spent materials or resources in the cycle [1]. Policies and regulations are forcing companies to promote sustainability and resource conservation, while targeting more independent and resilient supply chains. Subsequently, an economic benefit can be created by extending the lifetime of products instead of new manufacturing [2].

Nomenclature

BoL	Beginning of Life
MoL	Middle of Life
EoL	End of Life
CE	Circular Economy
RE	Reverse Engineering
SLR	Systematic literature review
LC	Life Cycle

For maintenance, repair and overhaul, it is often required to capture and assess the as-is state of the product. This is facilitated by the increased availability and easy use of sensors and devices such as 3D scanners. The field of Reverse Engineering (RE) provides methods for processing this captured data to produce parameterized, enriched digital models. The following steps are usually performed: Starting with the actual object (usually real object or part), as-is data is captured (e.g. laser scanning, photogrammetry), the data is processed (pre-processing, segmentation, feature detection, fitting, modelling), resulting in the digitized and parametrized model, ready for subsequent downstream applications [3,4]. In the framework of Digital Twins (DT), this model represents the digital shadow of a digital master instance [5].

As a single source of information, the DT combines different types of data of a product and allows decision-making on appropriate R-Strategies based on integrated data of Life Cycle Assessments (LCA). The 3D data integration of initial CAD models already provides important information, such as assembled parts, used materials and their amount or volume. However, this initial CAD model might simply not exist due to

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missing or outdated digitization in the year of manufacture. Worn-out mechatronic parts or entire products, that exhibit degradation or inferior functionality, usually deviate from their initial state. To extend the lifetime by repair or refurbishment, those deviations need to be digitized and assessed by RE methods. Furthermore, design decisions or manufacturing processes can be validated by gathering and extracting information during the product's LC. This refers to Feedback-to-Design and enables product optimization towards sustainability [4,5].

This paper focuses on the computational method of curve, surface and geometry reconstruction as a key step in RE to provide the geometrical basis for a DT, which has been identified as an enabler for sustainability in previous research. As such, the research contribution aims to establish a synergy between the well-established field of RE as a technological discipline and CE as a guiding principle. Accordingly, this paper aims to identify research gaps from the current state of the art to answer the following central research question: "How can the integration of 3D data in the DT support the application of R-Strategies to strengthen the CE?". Based on this question, an overview of scientific publications in relevant industrial applications is presented in a literature review. This will facilitate a comprehensive understanding of the potential of RE technology to extend the product's LC and promote greater sustainability.

2. Methodological approach

The methodological approach for conducting a systematic literature review (SLR) follows the PRISMA statement [6]. The first step of this methodology is to specify the eligibility criteria for the review and how studies were selected. Besides focusing on papers offering computer-aided and highly automated solutions, the literature is assessed regarding the following sub research questions (RQs):

- RQ1: What is the use case?
- RQ2: Which process steps of RE are applied and what is the technological focus?
- RQ3: Which phases of CE and R-Strategies can be addressed by geometric assessments?
- RQ4: What are limitations and gaps for future works?

The literature search was carried out in Scopus, one of the leading multidisciplinary databases for scientific research. Figure 1 shows the search string that summarises keywords. It is divided into three main sections. The first consists of the keywords: "digital twin", "circular economy" and "product development" and defines the overarching field of research. The second section introduces the data type, 3D point clouds from scanning applications. The last section narrows down the search string to the engineering procedure of RE, more precisely curve, surface and geometry reconstruction. The search is applied to title, abstract and keywords in the Scopus database and predominantly restricted to the subjects "Engineering".

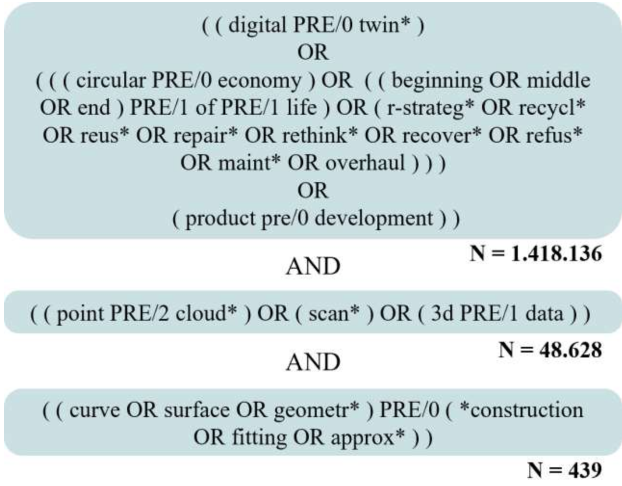

Figure 1. Scopus search string

A total of 439 scientific publications were identified by the database search in Scopus (as of the last database search on 20 October 2024). Figure 2 illustrates the process of sorting the identified papers. In the first phase, only titles, abstracts and keywords were examined, and papers were selected that dealt with mechatronic products, including classical mechanical engineering (e.g. automotive, aerospace, railway, shipbuilding, etc.). There are also many papers dealing with products with a high degree of customisation, such as textiles or medical products such as orthoses. A particularly well represented industry is the construction sector, because the technology of curve, surface and geometry reconstruction from point clouds has significant potential in this sector. The construction industry is faced with the challenge of mass refurbishment of existing buildings to reduce emissions and meet climate change targets. While the traditional manual creation of CAD models for refurbishment planning is reaching its limits, RE technologies are in high demand due to their ability to automate the digitisation of the large number of existing buildings. As a result, there is a high level of research into the technology in the construction industry, which explains the large number of resulting papers. It is not covered further in this paper due to major differences in the materials and construction elements used.

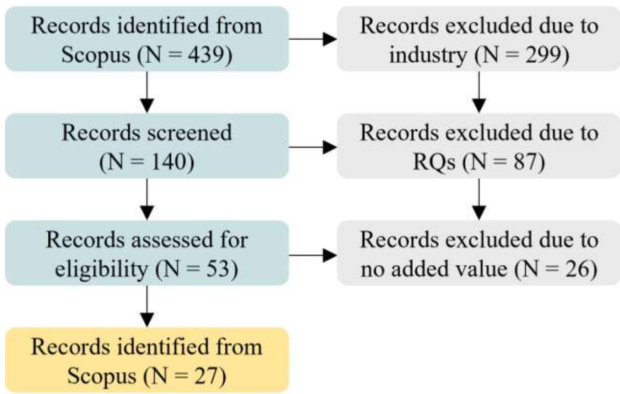

Figure 2. Selection of scientific papers

In the second stage of selection, based on title, abstract and keywords a further 87 papers were excluded as they did not provide sufficient information on the pre-defined RQs Thirdly, the final full-text analysis excluded papers with little or no differentiation from other papers and therefore no added value. From these, papers were selected that could provide more answers to the RQs. Finally, 27 papers remained for the systematic literature review.

3. Systematic Literature Review and results

Table 1 presents all researched scientific publications from the SLR. Each paper is listed by its year of publication, a basic description, and the overall aim of the literature reference. To answer the overall Research Questions, information about the use case (RQ1), the technological focus (RQ2), the R-strategy and LC phase (RQ3) and limitations as well as possible research gaps (RQ4) are presented. Potting et al. [1] define the following LC phases and associated R-Strategies:

- *Beginning of Life (BoL):* Refuse, rethink, reduce; Towards smarter product use or manufacture, e.g. more efficient products through Feedback-to-Design
- *Middle of Life (MoL):* Reuse, repair, refurbish, remanufacture, repurpose; e.g. extended product life through maintenance, repair or different use
- *End of Life (EoL):* Recycle, recover; using materials of products for other added value

3.1. Use case (RQ1)

Giving a better overview in Table 1, the use cases 'general mechatronic products', 'sheet metal (automotive)', 'gear', 'turbine blade', 'ship & aircraft hull', 'other large-scale industries', 'other industries' and 'others' have been categorised. Within these categories, the LC phases BoL, MoL and EoL were used for sorting, followed by the newest publication date.

Pos.	Ref.	Year	Description & Aim	RQ1 Use case	RQ2 Technological focus	RQ3 R-Strategy	RQ3 LC	RQ4 Limitations
General mechatronic products								
1	Shah et al. [7]	2019	Adaptation of parametric 2D sketches to point clouds; Work efficiency through automation	Gland (pump assembly)	Iterative parametric 2D-sketch adaption	Reduce	BoL	As-designed CAD must be available
2	Yin et al. [8]	2024	Additive manufacturing control via laser scanning and surface reconstruction; in-situ process control to reduce scrap	Additive manufactured parts	3D free form surface reconstruction	Reduce, repair, refurbish,	BoL, MoL	Limited modelling capacities
3	Kresslein et al. [9]	2018	Parametrized, feature-free surface reconstruction of arbitrary mesh data specifically for branched, organic structures or structural frames; for downstream applications, for topology optimization data	Mechanical parts	Automated recovery of cross-sectional shapes using centrally located curves	Reduce, repair	BoL, MoL	Accuracy, limited complexity of the part
4	Chan et al. [10]	2020	Novel geometric model for pipe elbow reconstruction; for maintenance purposes	Pipes, pipe elbow joints	Fitting parametrized geometry into point clouds	Repair, refurbish	MoL	Limited accuracy caused by occlusions
5	Fougerolle et al. [11]	2007	Recovering rational supershapes to represent mechanical parts; used to define simple and efficient reference model for recognition or comparison tasks in quality control	Mechanical parts in general	Rational supershapes (Gielis surface) to build an implicit function to represent	Reuse, repair	MoL	Reconstructed surfaces not directly usable in classical CAD
6	Bauer et al. [12]	2009	Reconstructing parametric models for reproducing an existing tube with bending machine; for remanufacturing products	Bent tubes	Center curve reconstruction, parametric modelling	-	EoL	Geometry: circular cross section and constant tube radius
Gear								
7	Kargunroudi et al. [13]	2022	Geometric reconstruction of spur gears using point cloud mapping analysis; Used to generate mold for flexible remanufacturing e.g. for heavy-duty equipment in the mining industry	Spur gears	manual 3D feature-based geometry reconstruction with automated parameter optimization	Reduce, repair	BoL, MoL	Not a fully automated process, manual CAD design required
8	Kumar et al. [14]	2013	Curve modelling of 3D scan data of spur gears; increasing work efficiency and reduce the product development cycle	Spur gears	Curve modelling	Rethink	MoL	Noisy scan data
9	Pang et al. [15]	2018	Low-cost laser scanning and gear parameter reconstruction system for assessment of cross-sectoral geometry	Gears	Sectional curves extraction of gears	Repair, refurbish	MoL	Gear parameter reconstruction; Gap: Automated geometry modelling
10	Feng et al. [16]	2018	Volume extraction and surface reconstruction of damaged gears; to Laser Metal Deposition (LMD) repair	Transmission gear	Data acquisition, registration, volume extraction	Refurbish	EoL	
Ship & aircraft hull								
11	Lafiosca et al. [17]	2022	Detection of dents in aircraft hull; Generation of synthetic training data; serves for maintenance and repair	Aircraft hull	CNN-based 3D (2.5D) point cloud segmentation	Repair	MoL	-
12	Pérez et al. [18]	2008	Approximation of ship hull cross-sections by 3D b spline curves; for overhaul, quality and shape assessment	Ship hull	B-spline curve approximation	Reduce, repair, remanufact.	BoL, MoL	Limited to cross-sections, not entire 3D surfaces
13	Duan et al. [19]	2023	3D ship hull surface reconstruction; for redesign and remanufacturing of new ships	Ship hull	Combination of RBF (via Deep Learning) and NURBS fitting	Reuse, recycling	MoL, EoL	Input data size / computational efficiency: down sampling required

Turbine blade								
14	Tian et al. [20]	2024	3D surface reconstruction of worn-out blade surface; basis for CAM planning of grinding process	Turbine blade (gas)	Full surface approximation by using cross-sectional curve fitting	Repair, refurbish	MoL	-
15	Ghorbani et al. [21]	2021	Automatic reconstruction of the profile section of air foil blade; used for quality inspection of air foil blades	Turbine blade (aero engine)	Curve-fitting (B-Spline)	Repair, refurbish	MoL	Noisy scan data
16	Ueda et al. [22]	2020	Boundary definition of worn region by curve approximation; for maintenance, quality assurance for product design	Turbine blade (not specified)	Curve fitting	Repair, refurbish	BoL, MoL	Only boundary curve reconstruction; only single defect processable
17	Wang et al. [23]	2013	Curve reconstructing for blade repairing; used for repair, which is preferable to replacement with a new blade due to the high costs	Turbine blade (aero engine)	Reconstruction of curves of cross sections	Repair, refurbish	MoL	Denoising the data
18	Piya et al. [24]	2011	Generating repair volumes for DMD process and virtual validation of planned repair process (CAM)	Turbine blade (gas)	Curve reconstruction (prominent cross sections, PCS), surface modelling, difference volume	Repair, refurbish	MoL	Waviness of generated surface
19	Li et al. [25]	2010	Boundary curve extraction and volumetric damage reconstruction; used for DED repairing	Turbine blade (gas)	surface approximation with double cubic Bezier surface	Repair, refurbish	MoL	Bezier approximation limitations
20	Gao et al. [26]	2008	3D volumetric defect reconstruction; defect repair through additive manufacturing (laser cladding) and subtractive machining for surface finish	Turbine blade (gas)	Curve fitting and surface modelling	Repair, refurbish	MoL	Accuracy: errors due to non-rigid clamping during scanning
Sheet metal (automotive)								
21	He et al. [27]	2020	Real-time 3D reconstruction of thin surface objects; to reduce memory usage, increase accuracy	Automotive sheet-metal parts	Improved truncated signed distance field (TSDF) method	Rethink	BoL	Topological errors due to thin surfaces
Other large-scale industries								
22	Tasistro-Hart et al. [28]	2019	Digital reconstruction of the geometry of a wind turbine blade; developing reusage applications for end-of-life wind blades in architecture and civil infrastructure applications	Turbine blade (wind)	Cross sectoral curves approximation, freeform surface modelling	Repurpose, recycling	EoL	Characteristics of cross sections need to be prior known
Other industries								
23	Jimeno-M. et al. [29]	2013	Surface reconstruction for curved contours of shoe lasts	Shoe last	Data acquisition, definition of number of landmarks	Rethink	BoL	Accuracy of current methods
24	Zhao et al. [30]	2024	Surface reconstruction and thickness error calculation of optical components; to detect and repair thickness errors (e.g. glass sheet for aircraft)	Optical equipment	Reconstruction with a complex curved surface	Repair, refurbish	BoL, MoL	-
Others								
25	Cui et al. [31]	2021	Automation of data acquisition using mobile robots and repair of 3D point cloud holes	Symmetrical objects	Automated data acquisition and 3D scan preprocessing	-	-	Conventional software provides poor point cloud repairing
26	Wang et al. [32]	2019	Reduce quantity of holes of triangulation surface of unoriented point clouds	Play figures	Preprocessing: triangulation	-	-	Topology errors
27	Jain et al. [33]	2018	Point cloud modification: to reduce noise and remove redundancies	Play figures	Preprocessing: Support vector regression (SVR)	-	-	Point cloud quality

Table 1. Overview of resulting papers

3.2. Technological focus (RQ2)

The results deal with different technological focuses, whereas the process of geometrical digitisation can be subdivided into curve (N=16), surface (N=10) and feature-based geometry (N=2) reconstruction. Furthermore, volume extraction (N=3) and general process steps of RE such as data acquisition by laser scanning (N=3), pre-processing (N=4) and segmentation (N=1) of 3D scan data are to be distinguished (Figure 3).

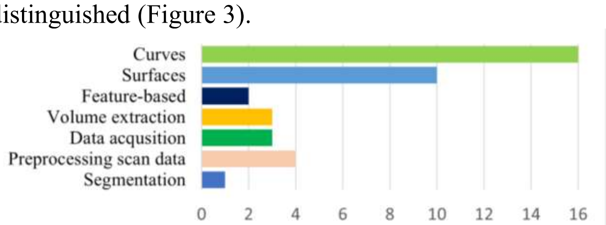

Figure 3. Technical focus

In general terms, curve and surface modelling, reconstruction or approximation involves fitting a Bezier, B-spline or NURBS curve or surface to an existing point cloud. Several publications aim to develop an actual CAD model based on 3D scan data of a turbine blade. This is because the original as-designed CAD models do not adequately account for deformations that occur during use, making them unsuitable for repair planning [23,26]. For example, Perez et al. deal with cross sectional curves to identify defects in ship hulls and ensure its surface quality [18]. Tian et al. use cross sectional curves as a preliminary step to freeform surface modelling and volume definition to realise repair of turbine blades by direct metal deposition [20]. Publications that deal with curve or boundary extraction perform point cloud processing in a way that the desired data points are extracted in order to subsequently approximate a Bezier curve to them [22,25]. Shah et al. present a different RE technique that describes the adaptation of parametrically dimensioned 2D sketches in CAD software to reference point clouds of parts or entire assemblies to be reconstructed using an optimisation algorithm [7]. Another stand-alone paper addresses the AI-supported preparation of the point cloud by a radial basis function neural network surface to mathematically approximate a NURBS surface in the second step [19]. Other publications have a technological focus on the pre-processing of scan data, dealing with point cloud quality and related measures such as hole repair, noise reduction and topology error removal [31–33].

3.3. Life Cycle and R-Strategies (RQ3)

The papers resulting from the SLR most often deal with MoL products (N=20). The MoL phase refers to usage, maintenance, repair and refitting of the product in order to extend its service life or improve its performance. Wang et al. state that turbine blades are susceptible to damage due to harsh operating conditions and ingress of foreign matter. Repair of these blades is often preferred to replacement due to the high cost of new parts [23,26].

This is followed by the number of papers that address the BoL phase (N=9), in which information about the as-is quality status of the existing product can be fed back into the product development phase. For example, Ueda et al. present a method for detecting the outline of damaged areas on turbine blades and approximate a curve to define the boundary. This geometric information about wear serves as feedback for product design in order to optimize the manufacturing process [22].

Publications dealing with EoL products (N=4) have the purpose of gaining geometric information through scan data before its material recycling or energy recovery. Bauer et al. aim to reproduce an existing tube with a bending machine after analysing its scan data and defining feature-based geometries such as arcs and line segments. This is employed for the generation of absent CAD data and the reproduction of EoL products that perform the same function [12].

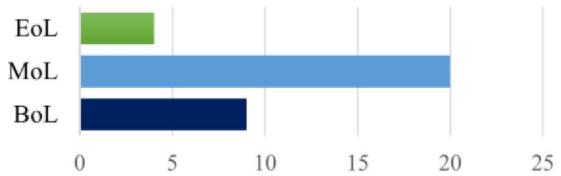

Figure 4. Life Cycle phases

3.4. Limitations (RQ4)

Limitations can be derived from the papers, leading to research gaps in the field. First, time-consuming manual work (N=2) and the demand for increasing automation within surface reconstruction was mentioned. Geometric difficulties (N=5) such as accuracy of curve or surface-fitting addresses the geometric challenge to Bézier-, B-Spline or NURBS curve and surface modelling. Point cloud quality (N=8) contains topological errors, noisy point cloud data and all difficulties with point cloud repairing. Computational efficiency (N=1), costs (N=1) and other limitations non-related to RE (N=1) are named within the resulting papers. It is worth mentioning that few papers would not display limitations and critically question their own technological solutions (Figure 5).

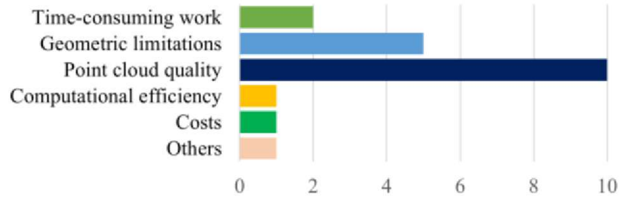

Figure 5. Limitations

4. Interpretation of results

The interpretation of results aims to define research gaps for future works. Since the main motivation of this paper is to research how RE, in particular curve, surface and geometry reconstruction can support CE, the aspect of R-Strategies is the first point to discuss. According to Potting et al. the BoL phase offers the greatest potential for improving the level of circularity of a product [1]. Adjustments in this phase can have a positive impact throughout the entire life of a product. It is therefore particularly important to transfer geometric information for quality control from the MoL and EoL phase to the BoL phase. Only 9 out of 27 papers use the information as feedback to improve the product development. There is a need for improving the digital continuity across all LC phases in order to transfer the as-is geometric information of the DT to strengthen the R-Strategies rethink, refuse and reduce.

In terms of its strong decision support for R-Strategies and the potential to support the Circular Economy, the DT should be used in less frequently represented use cases. Most use cases address free-form geometries like ship and aircraft hulls, automotive sheet metal parts, turbine blades, and even gears that present a complex curved shape. Significantly fewer publications deal with simple and predefined geometries of mechatronic components. The gap can be articulated as the need for more research into the parametric adaptation of 2D sketches and 3D models to point clouds to address the challenge of automating manual, time-consuming work and utilize the full potential of DTs.

Despite the rise of AI applications in all areas of engineering and manufacturing research, AI has only been represented in 2 of 27 papers found in the SLR, including the preprocessing of point clouds for surface reconstruction and point cloud segmentation. Therefore, more research is to be done to identify the whole potential of AI-based RE techniques.

5. Conclusion

In a SLR by using the PRISMA method, 27 publications on RE methods of curve, surface and geometry reconstruction of 3D point cloud data from scanning technology were found. The main research question was to investigate the potential of these methods for determining appropriate R-Strategies of mechatronic products. When defining the search string in the Scopus literature database, the engineering industry was differentiated from other industries. A particular strongly represented industry is the construction sector, which will be addressed in future works. The resulting scientific publications were presented in a table and clustered according to the sub research questions of use case (RQ1), technological focus (RQ2), R-strategies and LC phase (RQ3) and limitations (RQ4). All resulting papers were quantified according to these research questions and statistically presented in diagrams. Through the interpretation of the results, gaps in research were identified as the lack of implementation of Feedback-to-Design, the lack of application of parametric feature-based geometry reconstruction compared to free-form surface modelling, the need for automation to reduce time-consuming manual CAD modelling, and the lack of AI solutions. Increasing the efficiency of these methods will help ensure that mechatronic products can be kept in the LC longer, for example through repair. Additionally, it will allow products to be designed more sustainable by feeding wear information of all LC phases back into product design phase. The outlook for future work is to address the identified research gaps and develop more efficient methods to strengthen the Circular Economy and establish long-term resource conservation.

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