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Application of Reverse Engineering Methods for Manufacturing Lost Components of Rare European Car Engines

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Owner, Restoration of classic Japanese and European cars

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ABSTRACT

The article examines the application of reverse engineering methods to reproduce lost components for rare European internal combustion engines, given scarce original spare parts and disrupted supply chains. It is shown that the technological relevance of the problem is determined not only by the limited availability of warehouse stocks and the termination of production programs, but also by the high functional significance of individual parts, the loss of which effectively disables entire assemblies. The purpose of the work is to formalize a reproducible workflow, based on modern metrological and digital technologies, that enables moving from a single worn sample to an engineering-sound digital model and to small-batch, serial manufacturing. The scientific novelty of the article lies in a function-first approach to reverse engineering, which presupposes functional classification of lost parts, alignment of the measurement strategy with datums and critical surfaces, as well as the integration of multimodal metrology (manual methods, CMM, 3D scanning, industrial CT) with parametric CAD modeling, material and heat-treatment verification, and selection of the manufacturing route (machining, casting, additive processes). Key conclusions include the need to abandon direct copying of wear, prioritizing reconstruction of the design intent from interfaces and operating conditions; the expediency of iterative prototyping to verify geometry and packaging; and the requirement to close the reverse-engineering loop with full-scale control of geometry, leak-tightness, balance, and operability on a test bench. The article is intended for restoration engineers, remanufacturing specialists, and owners of rare European automobiles involved in the recovery and operation of historical engines.

KEYWORDS

reverse engineering, rare European engines, lost parts, functional analysis, metrology

INTRODUCTION

The loss or unavailability of individual parts for rare European engines is currently not a minor inconvenience for restorers but a systemic technological problem arising at the intersection of fleet ageing, limited production runs, and the breakdown of manufacturing supply chains. For many engines produced in small series, the loss of a part can renders the entire assembly inoperable: the structural role of a component may be disproportionately high, and substituting the closest analogue disrupts the geometry of interfaces, thermal clearances, or lubrication regimes. Contemporary scientific and engineering literature describes reverse engineering as a method for obtaining geometric information from a physical artefact and transforming it into a full-fledged digital model suitable for design and manufacturing, which is particularly valuable when the original design documentation has been lost or is inaccessible (Debnath et al., 2025).

Traditional ways of making up for the deficit, warehouse stocks, purchase of donor assemblies, or recourse to original manufacturers' heritage programs, often fail in the case of rare engines for reasons that are not only economic but also engineering in nature (Fan et al., 2023). Warehouse stocks for low-volume products are depleted rapidly, and after production ends, suppliers of materials and tooling often change or disappear, making even a small repeat batch technologically incomparable with the original. Donor parts, when available at all, usually have an unknown service history, hidden wear, and plastic deformation; in direct copying of such a sample, what is reproduced is not the nominal design but the accumulated error, which can then propagate through the assembly via tolerance chains. Finally, even major automotive groups that support heritage spare-parts lines are forced to limit both the nomenclature and volumes: public communications on supply programs for historic vehicles explicitly emphasize the selective nature of the range and its dependence on limited availability (Zhang et al., 2021).

The aim of this article is to present a reproducible, practically applicable reverse-engineering workflow for manufacturing lost components of rare European engines, grounded in contemporary measurement and digital reconstruction tools. The focus is on methods for acquiring source data (contact measurements, three-dimensional scanning, computed tomography for internal cavities), converting results into parametric models, selecting materials and heat-treatment regimes, and controlling the quality of finished parts. A key principle is to treat reverse engineering not as copying the shape but as restoring the design intent of the part through analysis of function, interfaces, and operating conditions, which corresponds to approaches described in work on the restoration and manufacture of parts for classic-car projects (Kyaw et al., 2023).

MATERIALS AND METHODOLOGY

The study of reverse engineering methods for manufacturing lost components of rare European engines is based on the analysis of a limited but purpose-built body of sources in metrology, remanufacturing, and automotive spare-part reproduction: at its core lie a systematic review of digital reconstruction and remanufacturing of mechanical components (Debnath et al., 2025), a review of practices for restoring automotive spare parts with emphasis on additive manufacturing (Dalpadulo et al., 2022), and an applied framework that combines reverse engineering with multi-criteria decision-making for a classic-car component (Kyaw et al., 2023). The theoretical frame of the article is defined by the function-first principle: reverse engineering is interpreted not as copying the form but as restoring the design intent through functional analysis, datum structure, and critical surfaces, which simultaneously reduces the risk of transferring wear and deformation of the only available sample into the nominal model, a risk highlighted in analyses of CAD-model accuracy based on measurement data (Turek et al., 2024). In addition, the work takes into account the broader context of scarcity and intermittent availability of rare parts, where the logic of replenishing losses is governed not only by economics but also by the instability of supply chains and the intermittent nature of demand for spare parts (Fan et al., 2023; Zhang et al., 2021).

Methodologically, the work combines a sequence of interconnected procedures: functional classification of lost parts by mode of operation (fastening/housing, components with internal channels, rotating elements, sealed interfaces, thermally loaded components); construction of a measurement logic and multimodal metrology with priority given to critical interfaces; followed by transition from mesh data to parametric CAD models with defined tolerances and rules of mutual location. For internal cavities and hidden channels, industrial X-ray computed tomography is a key tool, enabling simultaneous reconstruction of geometry and defect detection, which are critical for repeat manufacturing (Baumgärtner et al., 2023). In the materials-science block, the methodology treats material identification and choice of heat treatment as a fully-fledged part of reverse restoration: for drive and rotating components, emphasis is placed on coordinated control of strengthening and post-heat-treatment distortion (Liang et al., 2023), while for hot-zone parts, the focus is on confirming thermal-fatigue resistance and life under cyclic thermal loading (Wang et al., 2025).

RESULTS AND DISCUSSION

In the context of rare European engines, a lost part almost never refers to an abstract artefact but to a specific function within an assembly; consequently, the first step is to distinguish such parts by their functional role and by the surfaces that define the mutual positioning of components. Practice in digital reproduction of automotive spare parts shows that there is no universal route: the same set of measurement and manufacturing tools yields acceptable results for some components and leads to failures for others if functional differences and

operating conditions are ignored (Dalpadulo et al., 2022).

Fasteners, brackets, and housing components are generally defined by the geometry of datums and load paths; accordingly, the dominant factors are the accuracy of hole locations, coaxiality, and flatness of supporting faces, as well as fatigue strength and corrosion resistance of the material (Baumgärtner et al., 2023). Parts with channels for coolant, oil, or fuel are complicated by the fact that their functionality is governed not only by external interfaces but also by internal geometry: wall thicknesses, corner radii, continuity of cross-sections, and surface quality in sealing areas. In such cases, non-destructive tomography is considered an instrument that enables reconstruction of internal cavities and, simultaneously, reveals casting defects or inhomogeneities that are critical for repeat manufacturing (Baumgärtner et al., 2023).

Rotating components and elements of the valve-train drive impose the most stringent requirements on accuracy and materials, because small deviations in profile, runout, or surface hardness rapidly evolve into accelerated wear and noise, followed by failure. In such parts, geometry must not merely be similar but also kinematically compatible with the mating component, and the material must provide the required case-hardening depth and minimal distortion after heat treatment. Research on optimizing heat treatment of gear components emphasizes the conflict between strengthening and distortion and the necessity of controlling both parameters simultaneously (Liang et al., 2023). Sealed interfaces such as covers, flanges, and spacers appear simple, yet in practice they are highly sensitive to roughness, flatness, and local stresses induced by fasteners; their materials must be compatible with neighboring components in terms of thermal expansion and electrochemical behavior, or leaks and warping will result. Finally, components critical to the combustion process, pistons, valves, elements of the combustion chamber, and injectors, require not only high accuracy but also verified high-temperature strength, resistance to cyclic thermal loads, and appropriate heat treatment; for such parts, reverse reconstruction of geometry without a materials-science component is methodologically insufficient (Wang et al., 2025).

It is precisely the diversity of part types that dictates the need for functional analysis prior to measurement: the part's function and operating regime are first fixed, including load levels, temperature, contact pairs, the presence of abrasive in oil or coolant, and the nature of vibration. Critical surfaces are then identified, those that define datums and sealing, and a system of reference surfaces is constructed for subsequent reconstruction of geometry, so that the digital model reflects the structure of interfaces rather than accidental peculiarities of the sample. Approaches that combine functional analysis with digital reconstruction explicitly emphasize that, in spare-part manufacturing, what is often required is not literal copying but the reconstruction of design intent; otherwise, the operational error is reproduced rather than the original design (Baumgärtner et al., 2023).

The risk of a false truth is especially high when the only available sample is worn or deformed: in such a case, the measurement system faithfully records the current state of a surface, but this state may be the result of tooth wear, ovality of fits, bracket deflection, or crushing of a sealing edge, that is, effects that must not be transferred into the nominal model (Turek et al., 2024). Functional analysis must therefore culminate in a rule: everything may be measured, but confidence should be placed only in features consistent with the kinematics of the assembly, contact traces, and the logic of datums; uncertain regions should be reconstructed from mating components, symmetries, and engineering constraints embedded in the design (Debnath et al., 2025). Functional Classification of Lost Engine Parts for Digital Reproduction is shown in Table 1.

Table 1. Functional Classification of Lost Engine Parts for Digital Reproduction

Part type	Critical	Copying risk	Approach
Fasteners / brackets / housings	hole locations, coaxiality, flatness; fatigue/corrosion	assembly misalignment, cracking	datum-based measurement → CAD → datum/material verification
Flow-channel parts (coolant/oil/fuel)	internal geometry + sealing zones	looks OK outside but leaks/flow losses	CT/tomography + metrology → internal-cavity modeling
Rotating / timing drive parts	profile, runout; case hardening & heat-treat distortion	noise/wear → failure	high-accuracy metrology → heat treatment with distortion control
Sealed interfaces (covers/flanges/spacers)	roughness, flatness; material compatibility	leaks, warping	surface control → material match → clamp/thermal-cycle checks
Combustion-critical parts	high-temp strength, thermal cycling, correct heat treatment	geometry OK, material fails	geometry + materials validation + heat treatment + testing
Single worn sample (any part)	functional/datum logic > as-is shape	copying wear into nominal model	functional analysis → reconstruct via mates/constraints/symmetry

The acquisition of source data for reproducing a lost part begins not with the choice of instrument but with the construction of a measurement logic that follows from function and datums. Once critical surfaces and the risk of transferring wear into the model have been identified, metrology must provide two layers of information: accurate geometry of mating zones and a sufficiently detailed description of the overall form to reconstruct the design without guesswork. At this point, a paradox of reverse restoration becomes apparent: the more complex the shape, the stronger the temptation to capture everything at once, yet it is precisely the functional interfaces that demand the greatest rigor and local accuracy.

Manual measurements remain fundamental because they provide direct access to dimensions that define fits, clearances, and threaded connections. Micrometers and bore gauges reliably capture diameters and ovality; screw gauges and templates quickly distinguish standard from non-standard thread profiles; and simple techniques such as checking flatness with marking dye and a straightedge or assessing taper with a dial indicator often reveal deformations that digital methods will only later confirm. The value of manual metrology also lies in the discipline it imposes on datum selection: measurement requires explicit decisions about which surfaces define how the part lives in the assembly.

A coordinate-measuring machine is introduced when disparate dimensions must be transformed into a coherent geometric structure: axes, planes, hole centers, their mutual positions, and coaxiality. Unlike manual tools, a CMM already produces a model at the measurement stage: points do not merely record a surface, they form a system of datums to which all other data are tied. This approach is especially useful for brackets, covers, and flanges where mutual distances and orientations are critical, as well as for drive components where positional errors rapidly translate into misalignment and uneven wear.

Three-dimensional scanning with structured light or laser is appropriate for complex external shapes where manual measurements are too slow and an explicit analytical description of the surface is not required.

Scanning rapidly provides a dense representation of geometry, allowing the detection of overall curvature, smooth transitions, casting radii, and defects, but it is sensitive to reflective surfaces and is often insufficiently reliable for fitting cylinders and sealing edges. Consequently, scanning is typically used as a shape scaffold, while critical zones are additionally validated by contact measurements.

Photogrammetry is justified for large and less critical components where proportions and relative positions of features are important, but micron-level accuracy is unnecessary. Such a model may be useful in the first reconstruction or when the part cannot be brought to the laboratory: from a series of images, a photogrammetric model can be used to check packaging, detect collisions, and perform mock-ups. But it is rarely metrologically acceptable, as accuracy at thin edges and small holes is unreliable; it remains a starting point to be optimized.

Industrial computed tomography becomes critical once the part has internal channels, cavities, or hidden interfaces that cannot be measured without destroying the part. CT enables recovery of the internal geometry of manifolds, pump housings, and distributors, assessment of wall thicknesses, and detection of hidden defects that may recur in manufacturing if not accounted for. Best practices reduce to combining methods: critical interfaces are captured by contact and CMM, external geometry is acquired via scanning, internal features are refined by tomography, and then all datasets are brought into a unified datum system so that the digital model reflects not a mere sum of measurements but a single, functionally consistent geometry. Function-First Metrology Workflow for Lost-Part Reproduction is shown in Figure 1.

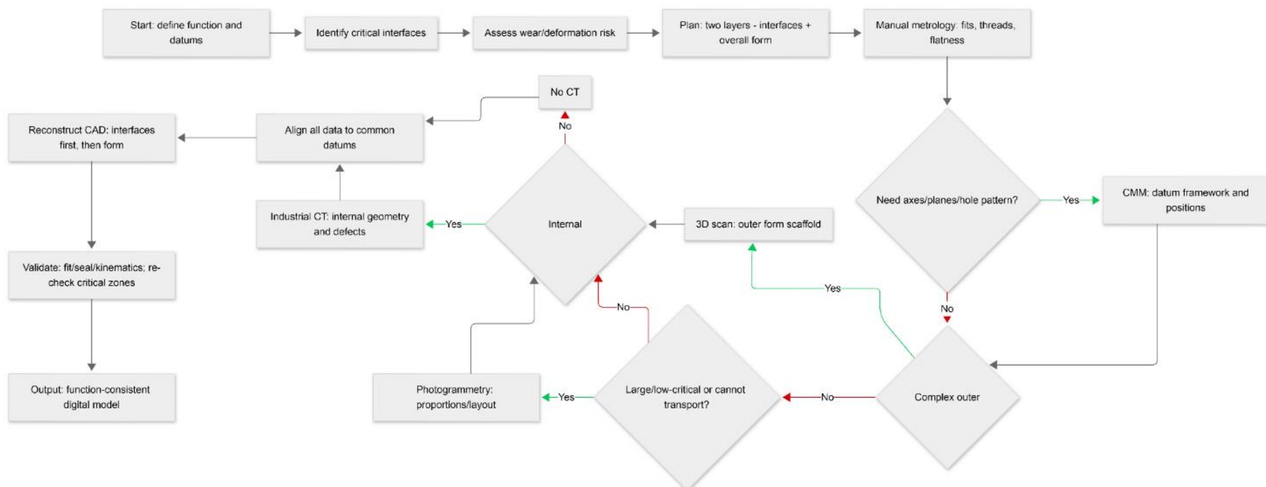

Fig. 1. Function-First Metrology Workflow for Lost-Part Reproduction

Once the desired geometry is captured, the following problem arises: a point cloud and mesh describe a part's geometry, but glare, contamination, registration errors, and local dropouts also appear as false positives in the data. Filters are used to remove isolated outliers, reduce high-frequency noise, close small holes, and remain sensitive to sharp discontinuities when they correspond to a functionally important feature of the part. It is important not to improve the surface to the point of sterility, as filtering eliminates small radii and thin ribs that usually define fits, flow direction, or sealing lines.

The data then must be transformed into a single coordinate system linked to the part's datums; otherwise, the digital form will remain visually convincing yet useless for assembly. Alignment to datums relies on surfaces previously identified as critical: mating planes, fitting-cylinder axes, and hole centers. Where geometry admits symmetry, it can be employed as a verification tool: a symmetric part rarely loses symmetry on its own, and pronounced asymmetry generally indicates deformation or a measurement error. Deformation control applies to thin-walled castings and brackets that are distorted by residual stress and service loads. In reverse restoration, there is no intention to restore the present curvature, but to restore a sound structure.

Because the acquisition uses a single view, and shadows cannot be scanned, scans must be stitched together. Care should be taken: if the registration is based only on the best point-to-point fit, the data can be subtly stretched. Proper stitching proceeds from stable areas to less reliable ones, with continuous verification of geometric completeness to avoid situations where a hidden cavity

or thin feature remains unscanned and is later reconstructed by guesswork. At this stage, blind areas are identified where re-acquisition by another method is necessary, because missing data are almost always costlier than an extra hour of measurement.

When the cleaned and aligned geometry is ready, the question arises: how faithfully does it correspond to the part's engineering model, and where are the risk zones? To address this, deviation analysis is performed between the scan data and the digital model, with incremental model refinement and verification that real interfaces are not being replaced by decorative smoothness. The deviation map is useful not only as a quality-control tool but also as a diagnostic instrument: a uniform shift often indicates a datum misalignment; local bulges point to wear or defects in the original part; and systematic waviness reflects features of the acquisition method or surface preparation. As a result, it becomes clear which regions can be described by simple geometric primitives and which require preservation of complex surface forms.

The transition from mesh to parametric model represents a shift from depiction to design, where every element must have meaning; otherwise, manufacturing degenerates into mere reproduction of randomness. A rational strategy is to construct functional surfaces first: fitting cylinders, mating planes, axes, holes, threaded zones, sealing belts, and only then envelop them with external morphology characteristic of casting or forming. This sequence protects against the temptation to tune interfaces to a distorted mesh, thereby transferring wear or deformation into the new part. At the stage of engineering interpretation, tolerances and rules of mutual location are defined for critical features so that the model describes not only shape but also requirements for its reproducibility; where necessary, corrections are incorporated for casting shrinkage, subsequent machining, and actual fits in the specific engine, where neighboring parts are also non-ideal.

Geometry alone does not guarantee operability; therefore, the materials-science track must proceed in parallel with model construction, especially for rotating parts, heavily loaded fasteners, and elements working in the hot zone. The new material is then selected based on chemical composition, hardness, and microstructure, as steels of the same composition may exhibit different microstructures and long-term endurance. If the original material cannot be identified, the new material is selected based on its compatibility with the other materials to avoid leakage, seizure, corrosion, and differences in thermal expansion coefficient. Heat treatment is chosen not by process name but by the required distribution of properties: where a tough core and hardened surface are needed; where dimensional stability after heating is critical; and where life under cyclic loading is decisive. It is at the interface between geometry and material that the outcome of reverse restoration is determined: a geometrically precise but improperly hardened part fails rapidly, whereas a strong yet geometrically inaccurate part begins to destroy the surrounding assembly; in both cases, restoration merely shifts the problem in time. Datum-Driven Scan-to-CAD and Material Validation Workflow is shown in Figure 2.

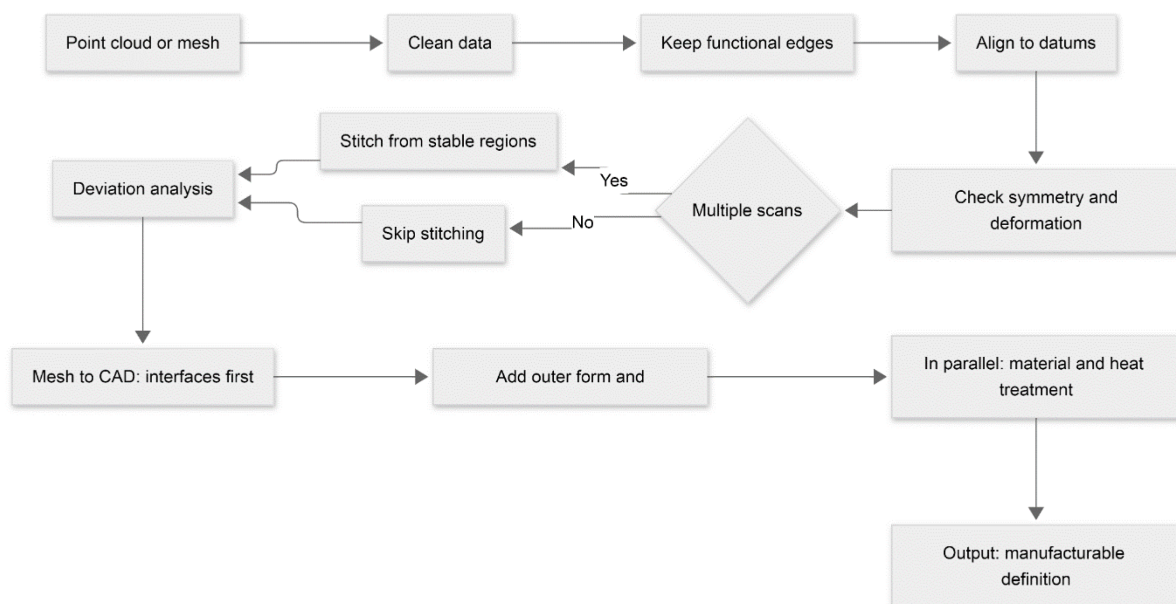

Fig. 2. Datum-Driven Scan-to-CAD and Material Validation Workflow

Selection of the manufacturing technology logically follows from what has already been established in reconstructing form and properties: which surfaces carry function, which regions permit approximation, where material and heat treatment define life, and where geometric compatibility and appearance dominate. Machining from solid stock is justified when accuracy and repeatability are critical, and the shape is relatively compact and does not require hidden cavities: this simplifies maintaining datums, controlling post-hardening distortion, and ensuring stable fits. This route is particularly rational for flanges, covers, spacers, brackets, and some drive elements; however, it is poorly aligned with thin-walled casting forms, often produces a foreign surface texture noticeable in authentic restorations, and results in excessive material and time consumption for complex outer contours.

When a part is originally cast, combining casting with subsequent machining is generally closer to the engineering logic of the original product, since it allows for light walls, smooth transitions, and characteristic ribs while ensuring accuracy on a limited set of functional surfaces. However, for tooling and shrinkage, the digital model must also include the technology restrictions, machining allowances, shrinkage areas used to accommodate shrinkage, and datums used for machining. If not, the digital model provides a geometry that is visually correct but unassemblable. For complex internal channels or when extremely small volumes or low quantities are required, metal additive manufacturing is sometimes used, especially when customary methods cannot create the cavity or when costs are prohibitively high. Because of this, the roughness of the inner surfaces, residual stresses, post-processing, and long-term dimensional stability of the part must be carefully controlled, or the part can become a source of leaks or accelerated wear. In this context, polymer printing serves not as a final material but as a tool: it accelerates assembly checks, provides positioning templates, master models for tooling, and expendable patterns for casting processes, enabling the separation of geometric verification from the cost of metal.

Comparison of technologies invariably reduces to trade-offs between accuracy, cost, lead time, and authenticity, yet these parameters are rarely independent. The higher the requirements on fits and mutual positioning, the greater the role of stable datums and subsequent machining, even if the base shape is obtained by casting or printing. The more important appearance and historical plausibility become, the more sense it makes to reproduce the technological signature of the original, including texture, radii, and wall-thickness distribution; at the same time, invisible engineering improvements, such as proper fillets at stress concentrators or a more predictable material, may be justified if they do not alter interfaces or violate the design intent. For rare engines, a strategy is often advantageous in which the first iteration is prioritized for speed and verification, and the final version for life and repeatability, because the cost of error grows non-linearly when failure of the surrounding assembly is more critical than the price of the replacement itself.

Quality control and testing must be embedded into the manufacturing route as rigorously as measurement is embedded into reverse restoration; otherwise, a correct model and a correct process provide no guarantee of operability. Geometric checks (coordinate measurement and repeat scanning) are not intended to reconstruct the point cloud, but to verify flatness, coaxiality, mutual hole positions, actual fits, and sealing belt statuses (where not only the form but also the surface roughness and microgeometry may be more important). For fluidic components, the leak-tightness of pressurized systems must be checked because pores or uncontrolled surfaces may only occur under working conditions. Balancing and checking the profiles of the components are critical for rotating parts. Minor profile deviations can result in vibrations and noise, as well as increased wear, leading to failure of the adjacent components. These functional tests, applied either in assembly or on the test bench, enable us to assess whether the geometry, the material, and the technological signature converge into a single operable system, but also to detect hidden interpretation errors, in which a part is formally compliant to the drawing but not to the engine's kinematics and thermal behavior.

CONCLUSION

The workflow considered demonstrates that successful manufacturing of lost components for rare European engines begins not with capturing the shape but with restoring the engineering logic of the part: its function, datums, and critical surfaces that govern assembly, leak-tightness, and life. For this reason, measurements, scanning, and tomography must be subordinated to functional classification and to rules governing data confidence. Otherwise, wear, deformation, and service history are imperceptibly transferred into the digital model rather than the nominal design. The transition to parametric CAD and the selection of manufacturing

technology continue the same logic: interfaces and tolerances first, form thereafter, followed by material and heat treatment as mandatory conditions for durability, particularly for rotating and thermally loaded components.

Subsequent selection of the production route (machining, casting with subsequent machining, additive methods) is rational only when it explicitly accounts for the trade-off between accuracy, authenticity, and repeatability, as well as the constraints of small batches and material availability. Practice shows that the manufacturing route most similar in appearance to the original does not always yield a part that can be assembled, whereas a technologically disciplined route with correct datums and distortion control more often ensures stable fits and predictable behavior within the assembly. At the same time, an iterative approach, rapid prototyping for verification of geometry and packaging, followed by a final, life-oriented version, reduces the cost of errors when damage to mating parts can be more critical than the cost of replacement.

Finally, embedded quality control closes the reverse engineering loop: it is not point clouds that need to match, but functional relationships, flatness, coaxiality, actual fits, leak-tightness, balance, and serviceability. When metrology, digital reconstruction, materials science, and testing are brought together under a function-first principle, reverse engineering is no longer artisanal copying but reproducible engineering, returning rare engines to operation without loss of reliability or cumulative error through a tolerance chain. Subsequently, the conclusion presents the key findings and practical recommendations for implementing the described approach.

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