ANALYSIS AND METHODOLOGICAL PROPOSAL

Photopolymerised sacrificial moulds for the indirect manufacture of ceramics and metals

Joint design of injection stability and aqueous removal with partial binder extraction

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Abstract

Indirect manufacturing with printed moulds allows the geometric freedom of photopolymerisation to be combined with the feedstocks used in ceramic and metal powder injection moulding. Its potential increases when the mould can be removed in water and the feedstock binder contains a fraction that is also extractable in that medium. The two operations can share a stage, although mould removal simultaneously changes water access and mechanical support for the part. This article analyses that interaction and proposes a design criterion connecting printed mould quality, stability during injection, the evolution of the part in the bath and quality after sintering. Published experimental evidence, manufacturer documentation and analytical deductions are distinguished. The article develops a mechanical approximation to explain the sensitivity of slender internal walls, a balance that separates mould removal from binder extraction, and a comparative protocol organised by process stage. The potential advantage of the indirect route lies in selecting separately the material that defines the geometry and the system that holds the powder together. Its usefulness must be demonstrated through geometry, integrity, time and cost per accepted part. This work is an analysis and methodological proposal; it reports no new experimental results and does not establish general superiority over direct printing.

Keywords: indirect additive manufacturing; vat photopolymerisation; sacrificial mould; CIM; MIM; partially soluble binder; aqueous debinding; dimensional stability; sintering.

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1 Introduction

Vat photopolymerisation allows a mould to be produced from a digital file without machining a dedicated metal cavity. The mould is then used to shape a feedstock, a mixture of powder and binder, which becomes a ceramic or metal part through binder removal, known as debinding, and sintering. The geometry is printed into the mould and transferred to the injected material. This separation allows the photopolymer to be tailored to the tooling requirements and the binder to the powder requirements. The shaped part that still contains binder is termed a green body.

The opportunity is particularly clear for prototypes, short production runs and geometries that are interlocked with the mould. A curved channel, an undercut cavity or a core intertwined with the part may prevent demoulding by opening two halves. Controlled removal of the mould material eliminates that opening constraint. Requirements for filling, venting, access for the removal medium and preservation of the part nevertheless remain [1,2].

Ceramic injection moulding, CIM, and metal injection moulding, MIM, are forms of powder injection moulding, PIM. Both require the binder to be removed while preserving the powder distribution. In a partially soluble system, the first extraction creates pores while an insoluble fraction maintains cohesion. This residual structure allows the part to be handled and the thermal treatment to be completed. Coupling this extraction with mould removal is attractive because it can reduce transfers and use a common process medium.

The scientific question is when that coupling preserves the geometry. During injection, the mould needs sufficient stiffness and strength; during removal, it must lose continuity without imposing unacceptable stresses on the part. At the same time, the feedstock loses some of the binder that provided its strength. Feasibility depends on the combined evolution of both materials, rather than solely on their individual solubility.

ER-49 developed the comparison of complete process chains using cost per accepted part and a route-selection record [3]. ER-85 distinguished process classes, feedstock preparation and stage-specific evidence; it also identified the limitations of HDT and the need to assess water access, residue and green-body recovery [4]. RP-02 provides the common qualification framework [5]. Building on these antecedents, this article develops the integrated aqueous operation: simultaneous loss of support and binder, separation of their contributions to mass loss, and a procedure for establishing the endpoint. The wall model illustrates how mould geometry affects both injection and removal. The contribution is a focused synthesis with a testable protocol, without claiming novelty for route classification, cost per accepted part or simply sharing a bath.

2 Scope and analytical method

A targeted review was conducted of primary studies on sacrificial moulds for CIM and MIM, direct ceramic manufacturing by photopolymerisation and aqueous removal of printed materials. ISO 75-1, ISO 75-2 and public technical documents for the materials used as examples were also consulted. The review closed on 7 November 2026. It is not intended as an exhaustive systematic review or a patentability assessment.

Sources were retained when they allowed identification of the material, the operation actually studied and the stage reached in the process chain. A demonstration of filling and demoulding is distinguished from one that includes debinding and sintering. Technical datasheets describe materials and reference conditions; they do not replace an experimental comparison between routes. Manufacturing observations from the development of 3Dresyns systems are used to formulate testable variables and criteria, without inferring proprietary compositions.

The mechanical deductions and balances presented are interpretative tools. They are not fitted to an experimental campaign on the 3Dresyn IM-HDT-WS and 3Dresyn EB1 assembly. The protocol in Section

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8 defines how to test the hypotheses and how to prevent a successful result at one stage from concealing a subsequent failure.

3 Available evidence and material selection

3.1 What has already been demonstrated

Wick-Joliat and colleagues produced sacrificial polyvinyl alcohol (PVA) moulds by filament extrusion and resin moulds by digital light processing (DLP) to shape complex ceramic geometries. The comparison favoured DLP for fine details and surface finish. In that study, the DLP resin was removed in an alkaline aqueous solution; the term aqueous removal therefore does not necessarily mean dissolution in neutral water [1].

Zhang and colleagues demonstrated a process chain for metal parts using a photopolymerised mould, a specific feedstock and near-zero-pressure injection, followed by mould removal, debinding and sintering [2]. Basso and colleagues studied a helix formed from a stainless steel suspension and analysed tooling deformation through tomography and simulation. The authors tabulate an injection pressure of 15 MPa and describe mould removal in an alkaline solution [6]. This second study provides evidence on filling and geometry; it does not include debinding or sintering.

Photopolymers removable in aqueous media have also been tested as moulds for other polymers. Liz-Basteiro and colleagues demonstrated sacrificial moulds for polycaprolactone and silicone [7]. Those results support the possibility of designing materials that retain integrity during use and can subsequently be removed. They do not automatically establish compatibility with a ceramic or metal feedstock or with its injection pressure.

Table 1. Scope of selected experimental demonstrations.

System studied	Published result	Transfer requiring validation
CIM with PVA or DLP [1]	Complex geometries and sintered parts.	Other powders, moulds and injection conditions.
Metal PIM at near-zero pressure [2]	Process chain through sintering and tracking of features.	Conventional high-pressure MIM and other binders.
Helix from a metal suspension [6]	Filling, deformation and removal in alkaline solution.	Part quality after sintering.
Photopolymerised mould removable in alkaline water [7]	Moulding of polycaprolactone and silicone.	CIM and MIM under their thermal and mechanical loads.

The conditions of each study form part of the evidence. Demonstrating one stage does not validate the complete chain.

3.2 Direct printing also permits binder improvements

Direct printing of ceramic or metal suspensions requires compatibility between powder loading, optical response, layer formation and green-body strength. A photopolymerised network may hinder organic-phase removal, particularly when decomposition products must travel long distances. Binder quantity matters, but its distribution, removal mechanism and pore connectivity also determine the outcome.

There is no universal maximum thickness of 2 mm for direct manufacturing. Zhang and colleagues obtained 15 mm alumina parts without cracks after debinding [8]. Marie and colleagues achieved wall thicknesses of 11 mm after debinding and 9 mm after sintering in silicon nitride [9]. These are results from specific systems and cycles, rather than guarantees transferable to any formulation.

It is also incorrect to assume that every photopolymerisable resin requires exclusively thermal debinding. Leite de Camargo and colleagues incorporated a water-extractable phase to facilitate two-

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stage removal in printed ceramics [10]. A relevant comparison must include both direct systems with mainly thermal removal and direct systems with aqueous pre-extraction.

3.3 Commercial materials as implementation examples

The documentation for 3Dresyn EB1 describes a partially water-soluble binder for preparing feedstocks, with an insoluble fraction intended for subsequent thermal removal. The 3Dresyn EB2G datasheet addresses highly polar powders, such as glass powders [11,12]. The two fractions serve different functions: initial extraction reduces the organic content while the residual fraction maintains cohesion. Complete binder removal in the bath should not be pursued if it causes the part to fail.

Within the same technical product range, 3Dresyn CDP-WS and 3Dresyn CDP-LDT WS provide photopolymerisable alternatives with an aqueous extraction stage [13,14]. Including them avoids attributing to injection an advantage that might instead arise from the binder extraction mechanism. 3Dresyn IM-HDT-WS is the sacrificial mould material used as an example; its datasheet positions it for injection and casting at elevated temperature and pressure [15]. That commercial positioning is distinguished from validation of the specific assembly.

These designations identify process functions. Component percentages, specific molecular mechanisms and performance equivalence between products are not inferred. Formulations for injection and for direct printing must be selected for the powder and the conditions of each route.

4 Producing a dimensionally stable mould

4.1 Resin level and contact with the print

In a printer that exposes through the bottom of the vat, part of the newly formed object remains in contact with liquid resin during the build. In soluble materials, that contact may plasticise the surface and increase tackiness. The 3Dresyns instructions for use recommend reducing the resin volume and maintaining a low level through automatic feeding [16].

The useful condition is the minimum operating level that allows complete, stable replenishment between layers. Reducing it below this value may leave areas unfed or disturb layer formation. An automatic feeder must compensate for consumption without introducing substantial level fluctuations, bubbles or thermal disturbances. The feed location also forms part of the adjustment.

For comparisons between prints, recording the liquid height, orientation and contact time of critical regions is proposed. In an approximation of uniform vertical advance, with a constant level and neglecting temporary emergence during separation, a region remains immersed for approximately the time needed to build a height equal to the liquid depth. Regional differences arise if the level or layer time changes, if the build ends before a region emerges, or if the geometry retains liquid. Lift motion and the adhering film also modify contact. That history must be recorded to relate it to surface feel, dimensions and local strength.

A low level reduces the fraction of immersed surface for some geometries, but does not by itself determine the volume of plasticised material. That volume also depends on liquid penetration and cure state. Evaluating the effect requires dimensional comparisons after cleaning and conditioning, as well as surface inspection immediately after printing.

4.2 Exposure calibration and geometric fidelity

Curing Rate Tables, CRT, relate exposure time to cured thickness for a formulation under specified optical conditions [17]. This information helps select an exposure that provides interlayer bonding without closing channels or thickening details. Excessive exposure may increase curing outside the intended volume, with particularly important consequences in Z and also at lateral boundaries.

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Calibration must describe irradiance at the working plane, spectral emission, position within the print area, temperature and the liquid thickness used in the test. If the available resin limits the cured thickness, the result is truncated. This limit may bias the estimated penetration depth; the liquid thickness is not itself a definition of that depth.

Measurement of patterns containing channels, walls and cavities representative of the mould after cleaning and post-curing is proposed. An isolated cure curve does not reproduce all the accumulated exposure in a multilayer build. When the printer permits only certain time increments, the actual programmed times must be recorded and the effective doses calculated, rather than assigning nominal doses that were not delivered.

The liquid level during printing and the thickness used to measure the CRT serve different purposes. The former must support manufacturing with controlled immersion; the latter must allow solid growth to be measured without constraining it and must describe the conditions of exchange with air. Transferring the calibration requires checking the result in the actual mould configuration.

4.3 Cleaning and post-curing

In the soluble systems considered here, water and alcohols may damage the freshly printed mould; initial cleaning must therefore be distinguished from final removal [16]. Cleaning Fluid WS1 Bio is formulated to remove surface resin from soluble or swellable prints [18]. Cleaning must be checked inside channels and cavities, where residual liquid may subsequently cure and alter the geometry.

The manufacturer's protocol includes immersion post-curing in fresh Cleaning Fluid WS1 Bio, separate from the washing liquid containing accumulated residues [16]. The proposed evaluation should record spectrum, irradiance, time, temperature and light access. Lack of tackiness is a useful surface criterion, but does not demonstrate uniform conversion throughout the wall. Optical attenuation and shadowed regions may produce different cure states.

The aim is to achieve a cure state that satisfies both stability during injection and subsequent removal. Higher conversion may improve stiffness or thermal response and, in some systems, increase brittleness or hinder removal. Maximum water resistance is not the objective of a sacrificial mould. The combined properties should be tested after the same conditioning that will precede injection [15,16].

Absorbed moisture and the elapsed time between post-curing and injection are included as control variables. To establish repeatability, a fixed conditioning procedure and comparison of mould mass and dimensions before use are proposed. No universal drying procedure is prescribed because temperature and time may also modify the material.

5 Stability during injection

5.1 Interpreting HDT

HDT is the temperature at which a specimen reaches a specified deformation under a defined flexural test. ISO 75-1 states that this result does not necessarily represent the maximum applicable temperature or directly predict final performance in service [19]. Feedstock temperature and mould HDT should therefore not be compared as equivalent limits.

The 3Dresyn IM-HDT-WS datasheet expresses HDT as “<160 °C” at 0.45 MPa [15]. This is an upper bound, with no central value, lower bound or specimen cure state reported. On its own, it does not locate the feedstock temperature relative to the actual mould HDT. To characterise the material intended for the process, measurement of HDT according to ISO 75-2, method B, on specimens with the same cure and conditioning as the mould is proposed [20]. The stress of 0.45 MPa pertains to the test and does not represent injection pressure. Insufficient cure may reduce HDT; quantifying the relationship between conversion and HDT requires both variables to be measured.

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Injecting a feedstock above the measured HDT may be feasible if geometry, support, pressure and contact duration keep the cavity within tolerance. Mould heating is transient and may differ from the temperature of the injected material. This possibility must be evaluated through local temperature and deformation during the cycle, particularly in tall, thin internal walls. The 3Dresyn EB1 datasheet recommends mixing the feedstock at 160 °C [11]; that preparation temperature is not necessarily the injection temperature or the transient temperature reached by the mould.

5.2 Why slender walls are critical

A simple approximation helps interpret the geometric effect. Consider a rectangular wall strip of free height h, thickness e and width b, fixed at its base. Under a uniform pressure difference Δp between its faces, it can be represented as a cantilever beam with a distributed load. Assuming linear elasticity, small deflections and a modulus E that remains constant during loading, the tip deflection is:

$$\delta = \frac{3\ \Delta p\, h^4}{2\ E\, e^3} \quad (1)$$

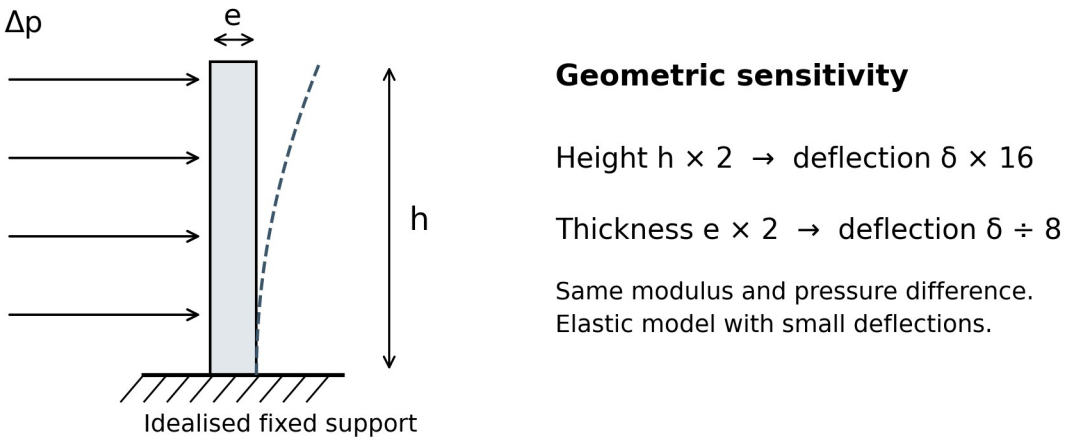

Figure 1. Idealisation of an internal wall and sensitivity of its deflection to geometry. Width b is perpendicular to the plane. The dashed displacement is schematic and not to scale. The factors shown follow from Equation 1; they are not experimental data.

The expression follows from the beam solution for a distributed load and the second moment of area of a rectangular section. It is a sensitivity approximation, rather than a validated mould simulation. It requires a strip slender enough to neglect shear deformation and a deflection small relative to h. A wide wall or one joined to other walls along its edges may require a plate model; Equation 1 is not a universally conservative bound. The relevant modulus corresponds to the thermal, cure and conditioning state during injection. Using a modulus measured at room temperature may underestimate deformation.

With other variables held constant, doubling the free height multiplies deflection by 16; doubling the thickness reduces it to one eighth. These factors follow from the model and are not experimental results. As an illustrative example, with E = 2 GPa, Δp = 1 MPa and h/e = 10, the equation gives δ/h = 0.75. That result exceeds the small-deflection regime and requires a different analysis; it is not a valid prediction for the product. The relationship explains why a short, supported wall may work where a long internal fin fails, even with the same resin and temperature.

The pressure difference that bends the wall must be used. The nominal machine pressure does not necessarily act as the full lateral load on every element. A wall between two cavities may experience transient differences during filling. Gate geometry, flow sequence and supports alter that load. The model also excludes creep, buckling, fracture, large deflections and plate constraints; those modes require testing or more comprehensive analysis.

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5.3 Designing support and water access

Thickening a wall may improve its stability during injection and prolong its removal. Where geometry permits, the function of containing pressure should therefore be separated from the function of defining the part surface. A reusable external support can sustain a thin sacrificial shell. Ribs and local supports can reduce the unsupported length without uniformly increasing the soluble mass.

The design must retain inlets and outlets for the aqueous medium after injection. A geometrically printable cavity may be infeasible if it traps a core without sufficient water access or an outlet for removal products. Support solutions must be evaluated together with bath access and feedstock filling constraints.

6 Mould removal and binder extraction in one aqueous operation

6.1 Two transformations that may overlap

After injection and the cooling needed to stabilise the feedstock, the assembly is immersed in the removal medium. Water acts on the mould and, wherever it reaches the part, may extract the soluble binder fraction. Extraction may begin before the entire mould has disappeared and continue afterwards. Integration means sharing an operation and coordinating its phases; it does not require both transformations to start or finish simultaneously.

The study by Wick-Joliat and colleagues already describes simultaneous PVA removal and pre-debinding. Their general procedure includes a further 4 to 6 days of extraction and at least 24 h of drying [1]. Removing material from both the mould and the binder in an aqueous medium therefore has precedents. The contribution proposed here is to determine compatibility criteria and the operation endpoint for a specific assembly.

During the overlap, the accessible area of the green body changes. Some regions may begin losing binder while others remain covered. Extraction need not be uniform. When a long wall or core is released, the distribution of supports also changes. The point at which the mould disappears may be more mechanically demanding than either the beginning or the end of the bath treatment.

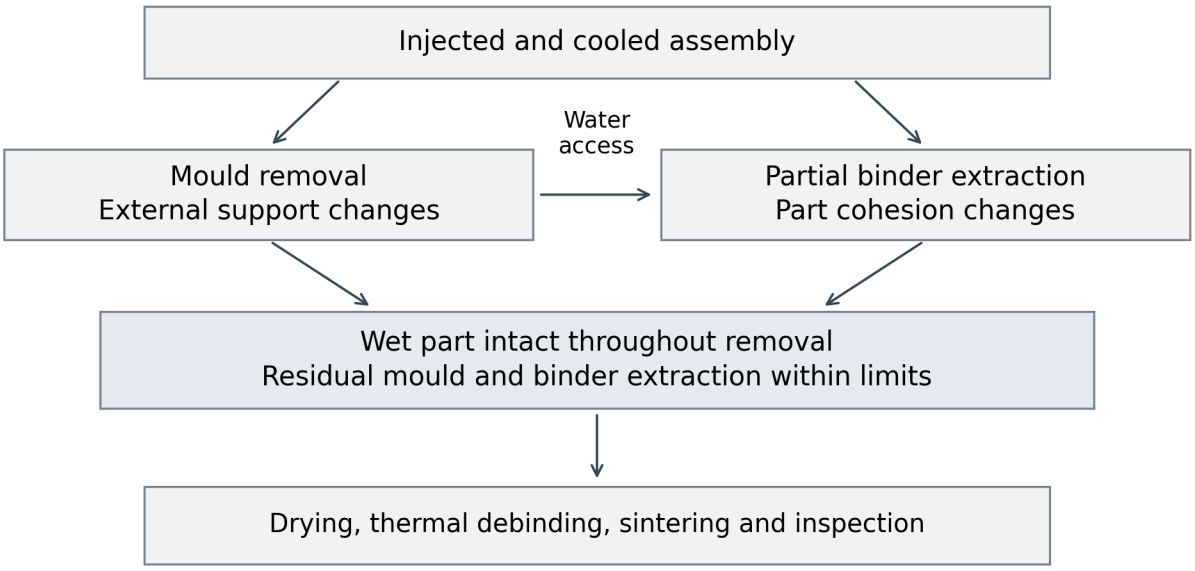

Figure 2. Coupling between mould removal and partial binder extraction. As removal progresses, water access and support change. Integrity must be maintained throughout the operation, as well as meeting the endpoint criteria. Proposed conceptual diagram.

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6.2 Assembly compatibility during loss of support

Studying the process as a progressive transfer of support from the mould to the residual feedstock structure and, where appropriate, to an auxiliary cradle is proposed. The part must withstand its own weight, handling, bath flow and stresses associated with swelling or non-uniform removal. The insoluble binder fraction contributes to that strength, but does not by itself ensure the survival of every geometry.

The integrity criterion must hold throughout the operation. Measuring strength before immersion and after drying is insufficient because a weaker intermediate state may occur. Interrupting tests at different times and evaluating the wet part using small loads and representative geometries is proposed. Residual load-bearing capacity must exceed the expected loading with a margin defined for the application.

Powder chemistry must also be compatible with the medium. For susceptible metals, water conditions, temperature and exposure may alter the surface or promote oxidation; other systems may exhibit leaching or pH changes. Medium selection must be verified with the specific powder and feedstock. Experience with one ceramic does not demonstrate compatibility with all alloys.

6.3 Separating mould removal from binder extraction

Assembly mass loss does not identify which material has been removed. Even in the ideal case, with no powder loss or retained water and with comparable dry reference states, the balance contains two contributions:

$$\Delta m_{total} = \Delta m_{mould} + \Delta m_{binder} \quad (2)$$

A single total mass loss is compatible with different combinations of mould removal and binder extraction. Wet measurements additionally include water absorption and retained liquid; if particles detach, powder loss is another contribution. Weighing the whole assembly therefore does not by itself demonstrate that the desired pre-extraction has been achieved.

Controls comprising an isolated mould, isolated feedstock and the moulded assembly are proposed under comparable conditions. They help identify behaviour and establish balances, but their rates should not simply be subtracted to predict the assembly: accessibility and bath composition change when both materials are present. Residual binder may be determined by thermogravimetry with an appropriate baseline for the powder and, where necessary, by selective analytical methods.

The extracted percentage must state its denominator. Removing a fraction of the soluble component is not equivalent to removing that same fraction of the total binder or total part mass. Dry mass and organic content must likewise be determined using a procedure that avoids attributing changes caused by drying, oxidation or particle loss to debinding. Leite de Camargo and colleagues removed up to 44 vol% of the added sucrose in water, with porous channels concentrated near the surfaces [10]. That percentage refers to the added component, and the observed distribution illustrates why global extraction does not establish local uniformity.

6.4 Endpoint of the integrated operation

The aqueous endpoint is established experimentally when mould removal to an acceptable residual level, target binder extraction, and preservation of part dimensions and integrity are all satisfied. Wet strength must remain sufficient throughout the preceding trajectory. Limits are set before testing, and inspection includes areas that are difficult to access.

Validation using groups of independent replicates withdrawn at increasing bath times, with closer intervals around the transition, is proposed. Where binder determination requires drying or destructive analysis, each replicate is assigned to a single time. Dimensions and integrity are first recorded in the wet state; the sample is then brought to a defined dry reference state for measurement of dimensions, residual mould material and residual binder using a validated selective method. Reversible water-induced changes are distinguished from permanent deformation. Internal residue is assessed by

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tomography if contrast and resolution permit detection, or by sectioning replicates and complementary analysis.

The result is the first tested time that satisfies the criteria within the temporal resolution and measurement uncertainty, rather than the exact instant of compliance. Integrity is also assessed at intermediate times and over a subsequent interval to delimit an operating window. Transfer to production requires validation of bath time, temperature, loading and renewal for the geometries and batches included. Non-destructive checks on each part are complemented by periodic residue and extraction controls; a clean surface does not by itself establish the internal state.

Bath temperature, volume and renewal are adjusted to the assembly. As mould and binder material enter the liquid, the medium surrounding the part changes. Keeping the same vessel may reduce handling, but does not require retaining increasingly loaded water. An integrated operation may include partial renewal, circulation, filtration or a final phase with fresh medium.

The 3Dresyn EB1 datasheet gives an aqueous treatment at 65 °C for 5 h as a reference [11]. This value neither fixes the time required for a 3Dresyn IM-HDT-WS mould enclosing a particular geometry nor demonstrates that all feedstock regions reach the same extraction level. The appropriate time must be established through the defined endpoint, followed by sufficient drying before thermal treatment.

7 Comparing routes through to the sintered part

The comparison must preserve part function, final material and acceptance criteria. Routes may use different optimised formulations and parameters, but those differences must be reported. A comparison of geometric capability, where one route may be infeasible, should be separated from a productivity comparison using a geometry that both routes can manufacture.

Table 2. Routes to distinguish in a manufacturing comparison.

Route	Shaping and extraction	Main consideration
Indirect with a durable mould	Injection, mould opening and binder extraction.	Demoulding feasibility and mould service life.
Indirect with a soluble mould	Injection and aqueous mould removal from the assembly.	Compatibility between loss of support and extraction.
Direct with mainly thermal binder removal	Photopolymerisation of the green body and thermal treatment.	Release of decomposition products without damage.
Direct with aqueous pre-extraction	Photopolymerisation, partial extraction and thermal stage.	Accessible porosity and residual cohesion.

All routes require drying where applicable, sintering and final acceptance to be defined. This is a process classification, not a quality ranking.

In the indirect route, the powder does not need to meet the same optical requirements as in a photopolymerisable suspension. This separation may facilitate the use of loadings, particle-size distributions or compositions that are difficult to print directly. Dispersion, feedstock stability and a viscosity compatible with filling remain necessary. A higher powder loading should not be assumed solely because injection is used.

Loading percentages must be compared by volume, with consistent definitions of the phases. A mass percentage of metal powder is not directly comparable with the same percentage of ceramic powder because of their different densities. Discussion of debinding requires quantification of the initial organic phase, the fraction removed before the furnace and the residual phase entering the thermal cycle.

Separation forces in printers that expose from below may impose a minimum strength requirement on a directly printed green body. The magnitude of that requirement depends on the separation mechanism,

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exposed area and formulation. It does not justify assigning a universal resin percentage to all direct manufacturing. The indirect route transfers some of these requirements to the mould and introduces those associated with filling and removal.

Following the criterion already used in ER-49 [3], cost per accepted part is adopted as the principal economic measure:

$$C_{accepted} = \frac{C_{batch}}{N_{accepted}} \quad (3)$$

Batch cost includes materials, preparation, tooling, printing, cleaning, post-curing, injection, aqueous treatment, drying, furnace processing, inspection and rework, with labour, energy and equipment depreciation allocated using declared criteria. Utilisation, batch size and outsourced services are recorded, avoiding double counting of any cost item. The number of accepted parts is determined after applying the same final requirements. If no part is accepted, the route is not viable for that batch and the quotient is not used as a finite cost.

Lead time is measured from design release to final acceptance. Operating time, equipment occupancy and elapsed time are recorded separately because some operations may run in parallel. An additional moulding stage may be offset by fewer rejected parts or less thermal processing time, but that offset must be measured. Faster printing alone does not imply faster delivery.

8 Proposed protocol for experimental validation

8.1 Hypotheses and comparisons

The first hypothesis is that a range of mould cure states and geometries exists that allows injection to be completed while retaining effective aqueous removal. The second is that the integrated operation can reduce handling or duration relative to a separate sequence without impairing integrity. The third is that part of the debinding advantage comes from the extractable binder and may be available in both direct and indirect routes.

To test the second hypothesis, comparison of equivalent assemblies using separate removal and extraction versus an integrated operation is proposed. The reference sequence must define how much binder is unintentionally extracted during mould removal; describing it as separate does not eliminate that physical overlap. For the third hypothesis, a predominantly thermal direct route and a direct route with aqueous pre-extraction should be included where processable. Optimisation of each route must be documented, and the same final quality criterion applied.

8.2 Geometries and variables

The campaign should begin with geometries that separate mechanisms: walls of different free heights and thicknesses for deformation; accessible cavities and tortuous channels for removal; and bodies of different thicknesses for binder extraction. A functional geometry combining those conditions should then be tested. Dimensions should be selected according to the application and metrological capability, without presenting an arbitrary size as a universal threshold.

The powder batch, particle-size distribution, volumetric loading, binder batch and condition, and photopolymer version must remain identifiable. When a variable cannot be matched between routes, its potential effect should be described. Ceramic and metal campaigns should be analysed separately.

Mould cure state, resin level and critical geometry should be varied in a planned manner. Relevant pressure and temperature histories, external support and filling should be recorded during injection. Bath records should include access, temperature, volume, composition and renewal. Manufacturing order should be alternated, with replicates distributed across independent builds to distinguish repeated readings from repeated manufacture.

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Table 3. Proposed measurements to trace the origin of defects.

Stage	Main measurements	Criterion to establish
Conditioned mould	Dimensions, surface, moisture and cure state.	Cavity within tolerance before injection.
Injection and cooling	Pressure, temperature, filling and deformation.	Preservation of critical walls and features.
Aqueous treatment	Mould residue, binder and integrity; replicates at increasing times, in declared wet and dry states.	Sufficient removal and extraction without intermediate damage.
Drying and thermal debinding	Stabilised mass, organic content and defects.	Reproducible state before sintering.
Sintered part	Dimensions, density, defects and functional properties.	Compliance with the same final requirement for each route.

Limits are set for each application. Isolated mould and feedstock controls complement, but do not replace, assembly measurements.

8.3 Metrology and acceptance

Geometry should be compared at successive points: conditioned mould, assembly after injection, released and dried part, debound part and sintered part. Tomography is useful when internal surfaces are inaccessible; optical or contact metrology can be used for open features. Method resolution and uncertainty must be appropriate for the tolerance being verified.

Criteria should be fixed before routes are compared. They must include dimensional deviations, cracks, porosity or density, relevant residues and functional properties for the application. Anisotropic shrinkage should be documented; uniform CAD compensation should be accepted only if justified by the results. Surface inspection of a sintered part does not replace assessment of internal defects when these are critical.

The report should present individual results, variation between builds and the denominators used to calculate acceptance at each stage. The number of replicates should be selected after a pilot campaign, according to variability and the difference of industrial interest. A time reduction should be interpreted as an improvement only if the required quality is maintained. No universal percentage saving or sample size independent of the application is proposed.

9 Analytical findings and discussion

9.1 Joint requirements for manufacturing and removal

The analysis identifies a feasibility condition consisting of requirements that must all be satisfied. The mould must retain its geometry after printing and conditioning; deformation during injection must remain within its allocated allowance; the part must maintain integrity during loss of support; and aqueous treatment must achieve its removal and extraction objectives. The process continues through drying, thermal debinding and sintering to final acceptance.

The methodological contribution is to specify the stage-resolved evidence of ER-85 and the qualification framework of RP-02 [4,5] for an operation in which the mould and binder change simultaneously. Mass loss from each material is distinguished, integrity is monitored during loss of support, and the endpoint is established using temporal replicates in defined measurement states. Selecting the mould solely by HDT, cleaning by surface feel or bath treatment by total mass loss yields incomplete indicators. Intermediate measurements locate the origin of a deviation and distinguish a printing failure from a failure during injection, extraction or sintering.

The design involves trade-offs. A thicker wall may reduce deformation and lengthen the removal path. More post-curing may improve thermal behaviour and alter subsequent removal. More intensive bath

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treatment may accelerate removal and increase loading on the wet part. The useful outcome is a configuration that satisfies all requirements, rather than the isolated maximum of a single property.

9.2 Tooling accessibility and geometric freedom

Liquid crystal display (LCD) printers priced below EUR 500 are available with a small pixel pitch. As a commercial reference, the ELEGOO Mars 5 Ultra listing advertises 18 µm in XY and prices below that threshold on the consultation date [21]. This specification describes image discretisation and equipment accessibility; it does not guarantee 18 µm accuracy in the mould or sintered part.

Lower investment at the printing stage may facilitate design iterations and distributed mould production. The complete chain requires equipment and control for injection, aqueous treatment, furnace processing and inspection. For interlocked geometries, the main value may be making demoulding possible, even when cost per mould is not the deciding criterion.

Durable printed moulds are an alternative when opening and mechanical release are feasible. Their service life is determined through use cycles and inspection. Sacrificial moulds consume one mould per operation but permit different geometries. Selection between the two options must account for part quantity and demoulding complexity without assuming a fixed photopolymer service life.

9.3 Aerospace relevance and limits of transfer

Ceramic cores that define internal cooling channels in turbine blades are a relevant application of indirect manufacturing. Wu and colleagues combined stereolithography and gelcasting to obtain complex ceramic cores [22]. This precedent demonstrates the value of printing the negative geometry, although it uses thermal removal and does not validate the aqueous operation proposed here.

Extrapolation to aerospace components requires final material properties, defect control and repeatability appropriate to the function. Producing a ceramic casting core and directly manufacturing a metal blade by MIM are different problems. Mould precision may contribute to the outcome, but does not replace validation of the component or its industrial route.

9.4 Limits of the evidence and contribution

The literature confirms the feasibility of specific combinations of sacrificial mould and feedstock. It does not establish the suitability of every high-pressure MIM system or commercial binder. The 3Dresyns documentation identifies candidate materials and procedures, but this article does not provide a complete comparative campaign of the 3Dresyn IM-HDT-WS and 3Dresyn EB1 assembly against all the routes considered.

Mould solubility, partially extractable binders and the use of a shared aqueous medium have precedents. ER-49, ER-85 and RP-02 already established comparison and qualification criteria [3,4,5]. This work specifies them for the coupling between loss of support and extraction through a mass balance, an operational endpoint and a mechanical explanation of slender-wall sensitivity. It establishes neither absolute priority for those concepts nor improved productivity or manufacturable thickness: those benefits require data under equivalent acceptance conditions.

10 Conclusions

Photopolymerised sacrificial moulds allow geometry generation to be separated from the selection of the binder that holds the powder together. This separation is particularly useful for components with undercuts or cores that prevent conventional demoulding. Its value must be evaluated on the final part, including the effects of extraction and sintering.

Producing a soluble mould requires resin-level control, exposure calibration, compatible cleaning and reproducible post-curing. An inexpensive printer may form part of that process, but nominal printer

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resolution does not by itself express the accuracy achieved. Dimensions must be verified after conditioning and at subsequent stages.

HDT is a characterisation value, rather than a universal maximum injection temperature. Stability depends on material state, transient heating, pressure difference and geometric support. The strong sensitivity of slender walls to their free height justifies designing the cavity, its supports and removal access together.

Mould dissolution and partial binder extraction can be integrated into an aqueous operation when the assembly maintains integrity throughout the loss of support. The endpoint is determined using replicates at defined times and distinct wet and dry states, separately verifying residual mould material, extracted binder and preserved geometry. Total mass loss is insufficient to identify those outcomes.

Comparison with direct printing must include formulations with aqueous pre-extraction and express powder loadings on comparable bases. The proposed criterion is to reduce time or cost per accepted part while maintaining final requirements. The protocol described allows that advantage to be tested and the geometries and conditions in which indirect manufacturing offers a verifiable industrial improvement to be identified.

Declarations

Conflict of interest. The author is affiliated with 3Dresyns by Resyner Technologies S.L., a manufacturer of materials mentioned in this article. Products are used as implementation examples, and their datasheets are distinguished from independent experimental evidence.

Data availability. This work does not incorporate a new experimental series. Public sources are identified in the references, and equations are defined in the text. The proposed comparisons and protocol should not be interpreted as tests already performed.

Technical confidentiality. Proprietary compositions are neither disclosed nor inferred from trade names.

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