COMMERCIAL, LITERATURE AND ECONOMIC STUDY

Commercial Feedstocks for MIM and CIM in Photopolymer Molds

Powder loading, binder removal, process compatibility and cost per accepted part

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3Dresyns by Resyner Technologies S.L.
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Conclusion. Extending the study is technically justified. Its value lies in selecting and comparing specific combinations of feedstock, mold and removal procedure, with traceable data and explicit limits. The available evidence does not establish that a single binder, mold or debinding system is superior for all metals and ceramics.

The study brings together 19 grouped commercial entries from 11 suppliers, 19 records on loading or removal, and 51 references. It distinguishes ready-to-mold pellets, binders for compounding, suspensions and direct printing routes. The industrial focus is on reusable and sacrificial molds produced by SLA, DLP or LCD, including economical platforms when their process has been qualified.

The analysis uses 40.00 EUR/kg for EB1 and 40.00 EUR/kg for IM-HDT-WS as project sponsor assumptions, not market quotations. It includes mass-volume conversions, a stage-based cost model and reproduced generic bronze scenarios. It provides no new experiments and does not demonstrate mechanical equivalence, supply availability or savings for a specific commercial combination.

Keywords: MIM; CIM; powder injection molding; feedstock; binder; debinding; sacrificial molds; photopolymerization; cost of quality.

1. Scope and distinction from the previous study

The question addressed is: **which commercial materials and removal routes can be used with photopolymer molds, under what conditions, and at what cost to obtain a conforming part?** The unit of comparison is the material-mold combination within a manufacturing chain, not an isolated brand.

Previous study [1]	Extension developed here
Mold stability during filling and aqueous removal with partial binder extraction.	Traceable commercial inventory of feedstocks, binders and suspensions; identified denominators and formulations.
Model of deformation, loss of support and removal measurement.	Comparison of aqueous, solvent, catalytic and thermal routes; limits on transfer between suppliers.
Proposed qualification procedure and cost framework.	Normalization of loadings and prices, distinction between stage costs and overall yield, and a material-specific testing program.

Injection into sacrificial molds, their use with several ceramics and aqueous extraction have already been reported [28-31]. PIM fundamentals and debinding routes form an established field covered by German and Bose and by the Heaney handbooks [39-41]; Enneti reviews thermal debinding problems [42]. Cost per accepted part is likewise not presented as a new principle. The proposed contribution is to organize heterogeneous commercial evidence and connect it to compatibility, quality and reproducible economic decisions.

Basso investigates how particle size distribution changes rheology for low-pressure PIM [43]. Novák compares PIM, MEX and DMLS in 17-4PH steel [44], without evaluating photopolymer molds. These precedents rule out claiming the general integration of additive manufacturing and PIM as a first.

Boundaries of the analysis

MIM denotes metal injection molding and CIM ceramic injection molding. PIM encompasses both; IM is the general term for injection molding. Glass and functional materials are included where relevant. Casting remains the reference for specific metallic alloys. For ceramics, the comparators are conventional CIM, pressing and machining, casting or direct additive manufacturing, depending on geometry and function.

This is a targeted documentary review with economic scenarios, not an exhaustive systematic review or product validation. Suppliers were not contacted and no new quotations were received. The initial review cutoff was November 7, 2026; commercial coverage of 3Dresyns powder-containing slurries and custom formulations was added on November 8 [48-51].

2. Review method and strength of evidence

Official manufacturer sources and primary studies identifying the material, formulation or process were consulted. The commercial grade, source date, percentage basis and extent of access were recorded. Tables retain the category of each datum: supplier-reported, measured in a study, calculated or assumed.

Category	What it supports	What it does not support
Commercial datasheet or catalog	The manufacturer declares a product or process and indicative conditions.	That all its properties have been independently verified or tested in printed molds.
Measurement in a primary study	That material or sample produced the reported result under that protocol.	That the current lot has the same composition or that the result covers another geometry.
Reproducible calculation	A consequence of the stated values and assumptions.	That the process achieves the entered yield or density.
ND: not located	The datum was not obtained in the sources consulted.	That the manufacturer cannot provide it on request or under an agreement.

Proprietary recipes have not been reconstructed from trade names. A safety data sheet may omit components not subject to disclosure and report ranges; it is not a composition specification. Neither powder purity nor sintered-part density is interpreted as the solids loading of the feedstock.

Coverage and limitations

The selection covers manufacturers of metal and ceramic feedstocks and suppliers of binders and direct printing suspensions. Glassomer is distinguished as a supplier of glass materials and solutions, without assuming open-market availability of every granular product. Fraunhofer IKTS is used as a technical and development source, not as a raw-material catalog [22-23,34].

The source register identifies articles with partial access. Data from 2016, 2017 and 2019 are retained as dated precedents. An old PDF remaining on a website does not establish that the same grade is still available. The CSV files allow a datum to be replaced when a more recent datasheet or quotation becomes available. For the handbooks [39-41], identification, descriptions or contents were consulted, not complete chapters; [42] is used only through its primary abstract. Conference and research papers [43-44] were retrieved in full.

3. Pellets, binders and slurries: what is being purchased

Format	Content and function	Consequence for comparison
MIM/CIM granules or pellets	Powder and binder system already mixed and pelletized; softened for molding.	The price includes powder, binder, formulation, homogenization and supplier quality control.
Commercial powder-free binder	Organic system to which the selected powder is added; examples include EB1, EB2G and some Embemould products.	Add powder, mixing, pelletizing where applicable, lot control and development costs.
Hot thermoplastic suspension	Powder dispersed in a molten vehicle, often used at lower pressure.	Slurry does not imply water, photocuring or a low binder fraction.
Aqueous or solvent suspension	Powder, carrier liquid, dispersants and, depending on the route, binder or gelling agent.	The non-powder fraction includes liquid; it is not entirely binder.
Photopolymerizable suspension	Powder and a reactive phase consolidated by light.	Changing the mold does not turn it into thermoplastic pellets. Optical access and adequate curing are required.
Pressing granulate	Agglomerated powder with additives for die filling and compaction.	Its granular form does not establish suitability for injection molding.

A commercial comparison must specify whether the purchase is a ready-to-mold product, a custom formulation, a binder or a manufacturing service. Comparing one kilogram of EB1 with one kilogram of Catamold as though they contain the same amount of metal is invalid [2-6,15-16].

In a closed, nonporous cavity, a slip does not consolidate through the same mechanism as in an absorbent mold. Gelation, drainage, vehicle removal or another mechanism must be designed. An aqueous suspension may attack a water-soluble mold during filling itself. These compatibility questions must be resolved before calculating productivity.

4. Percentages: four different denominators

Every percentage must specify the quantity, denominator and method. Binder here means the binder system, which may contain polymers, waxes, plasticizers and additives. The entire non-powder fraction may be called binder only when the formulation and mass balance justify it.

Quantity	Definition	Error to avoid
Powder mass fraction, w_p	Powder mass / total feedstock mass.	Confusing 90 wt.% with 90 vol.%.
Powder volume fraction, φ_p	Powder volume / total volume, using the stated densities and reference state.	Converting without knowing the effective binder density.
Binder extracted	Mass removed relative to initial binder or initial part mass: specify which.	Calling a loss of 50% of a soluble fraction a 50% binder content.
Dry solids in a slurry	Fraction remaining after vehicle separation by a defined method.	Assigning all loss of water, solvent or monomer to binder.

Conversion for an ideal binary mixture

$$\varphi_p = (w_p / \rho_p) / [(w_p / \rho_p) + ((1 - w_p) / \rho_\beta)]$$
$$w_p = (\varphi_p \rho_p) / [\varphi_p \rho_p + (1 - \varphi_p) \rho_\beta]$$

ρ_p and ρ_β are the true phase densities in compatible reference states. Neither the apparent bulk density of loose powder nor the bulk density of a pellet bed is used in the conversion. For systems containing water, solvent or other components, their volumes must be included and any assumption of volume additivity stated.

The economic scenario uses **90.0 wt.% powder and 10.0 wt.% binder on a total-mass basis**. Adding 10 g of binder to 100 g of powder is a different case: 9.09 wt.% binder in 110 g. These dosing conventions must not be interchanged.

TGA measures mass change. Interpreting it as composition requires consideration of moisture, volatiles, ash and possible powder-atmosphere reactions. In metals, oxidation may offset part of the organic mass loss. Complements calculated as 100 minus powder loading are identified as calculations, not analyses of each polymer.

5. What changes from bronze to ceramics

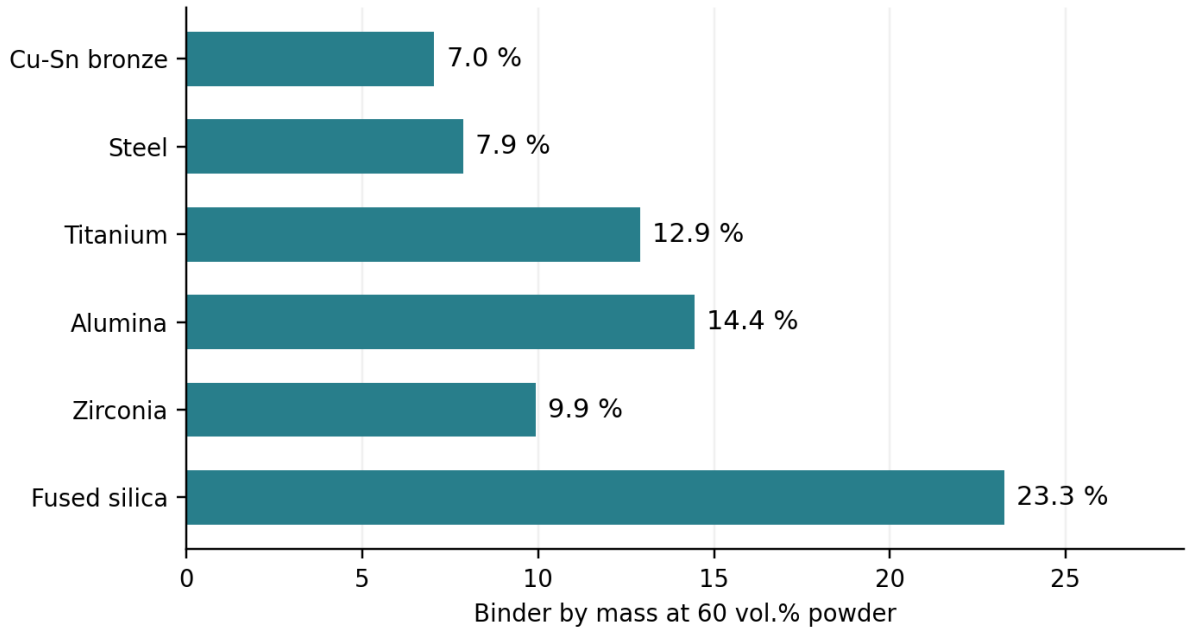

Figure 1. Illustrative calculation at 60 vol.% powder. Assumed binder density: 1.00 g/cm³. These are not recipes or certified EB1 or EB2G densities.

Powder	Assumed ρ_p (g/cm³)	Powder vol.% at 90.0 wt.%	Binder wt.% at 60 vol.%
Cu-Sn bronze	8.80	50.6 %	7.0 %
Aluminum bronze	7.60	54.2 %	8.1 %
Steel	7.80	53.6 %	7.9 %
Titanium	4.50	66.7 %	12.9 %
Alumina	3.95	69.5 %	14.4 %
Zirconia	6.05	59.8 %	9.9 %
Fused silica	2.20	80.4 %	23.3 %
WC-Co, illustrative	14.50	38.3 %	4.4 %

Under these assumptions, the mixture gives 50.6 vol.% powder for Cu-Sn, 69.5 vol.% for alumina and 80.4 vol.% for fused silica. Transferring a mass-based formulation may exceed the processable loading of another powder. The calculation does not determine an optimum.

5.1. Sensitivity to binder density

The effective density of the binder system is not a dispensable detail. The range 0.90-1.40 g/cm³ is a hypothetical sensitivity analysis, not an EB1 or EB2G specification or a measurement of all commercial binders. The powder mass fraction is held at 90.0 %.

Material	Powder vol.% ρ_β = 0.90	Powder vol.% ρ_β = 1.00	Powder vol.% ρ_β = 1.40
Cu-Sn bronze	47.9 %	50.6 %	58.9 %
Aluminum bronze	51.6 %	54.2 %	62.4 %
Steel	50.9 %	53.6 %	61.8 %
Titanium	64.3 %	66.7 %	73.7 %
Alumina	67.2 %	69.5 %	76.1 %
Zirconia	57.2 %	59.8 %	67.6 %
Fused silica	78.6 %	80.4 %	85.1 %
WC-Co, illustrative	35.8 %	38.3 %	46.5 %

Changing density changes the converted value but does not eliminate differences between materials. Mixtures with equal powder mass fractions remain unequal in volume fraction. A POM-system density must not be replaced by 1 g/cm³ without justification.

The file sensibilidad_densidad.csv also includes the binder mass fraction required to reach 60 vol.% powder. This band is an analysis of assumptions, not a confidence interval or a qualified formulation window.

Before compounding, measure or document each phase density in a compatible state, homogeneity, rheology and critical loading. A correct arithmetic conversion does not demonstrate that the mixture can be injected, demolded or sintered without defects.

6. Published loadings: metals and historical data

System / source	Reported powder	Binder or remaining fraction	Limit of use
Catamold 316L-A [24]	≈90 wt.%; ≈63 vol.%	≈10 wt.%; ≈37 vol.%, by subtraction.	2016 study; not a current lot specification.
Catamold TZP-A, zirconia [24]	≈80 wt.%; ≈47 vol.%	≈20 wt.%; ≈53 vol.%, by subtraction.	Historical ceramic grade; current offer not verified.
PolyMIM 316L D 110 E and 17-4PH D 110 E [25]	>60 vol.%	<40 vol.% nonmetallic.	No exact recipe or loading for the entire product range.
Catamold 316 L G and 17-4PH G [25]	>60 vol.%	<40 vol.% nonmetallic.	Rheological comparison specific to these materials.
ADVAMET, thermal guide [7]	Not inferred.	6.0-8.3% binder; basis not explicit in the text.	Confirm wt.%, grade and dry state before normalization.
316L + LDPE/paraffin [30]	70 vol.%	30 vol.% remaining.	Experimental mixture; mean powder size 50 µm; evaluated without sintering.

The paired Catamold values [24] imply binder densities of 1.495 and 1.341 g/cm³, using 7.9 g/cm³ for 316L and 6.05 g/cm³ for zirconia. This is an internal consistency check using $\rho_\beta = \rho_p \varphi_p (1 - w_p) / [w_p (1 - \varphi_p)]$, not an independent measurement or a reconstruction of the recipe.

The 2019 comparison identifies different particle size distributions among the metallic feedstocks studied. A size range of 1-10 µm is not a universal requirement for every process. Nor does injecting a coarser powder demonstrate equivalent final performance [25,30,43]. MPIF describes powders typically below 20 µm, without establishing a universal 1-10 µm requirement [45].

ND means that a usable value was not located, not that the manufacturer has been shown to lack the information. The extended loading table is supplied as a CSV with status, locator and a caution for each row.

7. Published loadings: ceramics and suspensions

System / source	Powder datum	Complement or extraction	Scope
INMAFEED K1008 [26]	84.5 wt.%, TGA.	15.5 wt.% nonceramic.	2017 sample.
INMAFEED K1010 [26]	85.3 wt.%, TGA.	14.7 wt.% nonceramic.	2017 sample; not a current contractual value.
INMAFEED K1013 [26]	84.1 wt.%, TGA.	15.9 wt.% nonceramic.	Does not identify individual organic components.
INMAFEED K1009, zirconia [27]	84 wt.%, TGA.	16 wt.% nonceramic.	Extrusion study published in 2026.
K1010 and K3012 in Didilis [28]	80-85 wt.%; 50-60 vol.%	15-20 wt.%; 40-50 vol.%	Reported ranges; do not arbitrarily pair endpoints.
Alumina + K83/K83G 1:1 [26]	85 wt.% nominal.	15 wt.% nominal binder.	Feedstock prepared by the authors with commercial binders.
New LithaLox alumina [20]	55 vol.% declared.	45 vol.% nonceramic.	2026 announcement; do not generalize to zirconia.
INMAPOM K3030 [37-38]	Not inferred.	15.8% DE 2017 / 16.6% EN 2024 catalytic mass loss.	Different revisions; do not attribute the difference solely to language.

For K3030, the retrieved German datasheet is dated November 2017 and the English one July 2024. Their catalytic mass losses are 15.8% and 16.6%, respectively. These are not averaged and no recipe change is inferred. Both report approximately 16.6% shrinkage and a mold factor of 1.20; interpreting this as linear shrinkage follows from that factor ($1 - 1/1.20 \approx 16.7\%$), not from an explicit label [37-38].

Didilis calls K3012 “INMAFEED” and describes a POM binder; the manufacturer places it in INMAPOM. The article designation is retained when citing its results and the supplier designation when identifying the product. The two sources are not combined into a certificate [28,36]. As an arithmetic consistency check, alumina at 80-85 wt.% with $\rho_p = 3.95$ and $\rho_\beta = 1$ g/cm³ gives approximately 50.3-58.9 vol.%; this does not assign paired endpoints to its two grades.

8. Commercial landscape: metallic systems

Supplier / family	Format and route	Available datum	Relevance to printed molds
BASF / Catamold	MIM pellets; catalytic + thermal removal of residual binder	ND for current individual grades	Commercial product; test mold and route for each grade [2,3,24,25]
polyMIM / polyMIM	Ready-to-mold feedstock; water + thermal removal of residual binder	>60 vol.% in four compounds in the 2019 study, two from polyMIM	Do not extend to the entire catalog or every lot [4,25]
polyMIM / polyPOM	Ready-to-mold feedstock; catalytic, with cycle and residue removal depending on grade	ND	Do not confuse with aqueous polyMIM [5]
AMP / ADVAMET	MIM feedstock; thermal, confirm alternatives by grade	6.0-8.3% binder in an example; basis not explicit	Published cycle for small, well-supported parts [6,7]
AMP / ADVACAT	MIM feedstock; catalytic, with cycle and residue removal depending on grade	ND	Different formulation from ADVAMET [6]
Micro MIM Japan / Taisei Kogyo; MMJ-316L-070 / MMJ-17-4PH-070	MIM pellets; thermal route with no additional extraction declared	ND; TG is not digitized to invent a recipe	Datasheet distinguishes indicative values from guarantees [12,13]

What to compare within the same alloy

To isolate tooling effects, use the same feedstock and lot in a reference metal mold and in the printed mold. To compare suppliers, hold final composition, geometry, finish and functional requirements constant. Otherwise, a difference attributed to the binder may originate in the powder, heat treatment or acceptance criteria.

Catamold lists several steels in its public portfolio, including 316L, 17-4PH and other families [2]. This does not establish the supply of Cu-Sn bronze or aluminum bronze. For these two cases, the availability of a commercial ready-to-inject mixture remains to be confirmed; a steel price is not used as a substitute.

A thermal-only route is an actual commercial option, as declared by Micro MIM Japan [12]. Eliminating the binder extraction bath may simplify equipment, but does not remove the need to remove a sacrificial mold or the heating, support and decomposition-product evacuation requirements.

9. Commercial landscape: ceramic systems

Supplier / family	Declared route	Loading located	Technical interpretation
INMATEC / INMAFEED	Water + thermal	Historical measured examples: 84.0-85.3 wt.% powder	Identify grade, year and lot; not a universal value [8,9,26,27]
INMATEC / INMAFLOW	Acetone + thermal	ND in the program consulted	Evaluate solvent effects on mold and part [10]
INMATEC / INMAPOM	Declared single-stage catalytic route; verify residue	K3030: 15.8% DE 2017 / 16.6% EN 2024 mass loss	Not a complete recipe; these are different revisions [36,37,38]
KRAHN Ceramics / Embemould / kcmix	Water, acetone, thermal or catalytic, depending on system	Generic value ND; research mixture identified separately	Agree processable composition and route with supplier [11,26]
CERMET Feedstock / Custom CIM and MIM ranges	Various routes declared by supplier	ND	Declared commercial coverage; comparable grade-specific datasheets are missing [14]

The K1010 datasheet describes water extraction followed by thermal removal. The INMAFLOW program specifies acetone and a thermal stage. INMAPOM declares single-stage catalytic debinding; that description is respected and the residue must be verified, without inventing a separate second operation for every grade [9-10,36-37].

Several routes within one manufacturer enable controlled comparisons, but grades must not be assumed identical apart from binder: powder, additives, loading and sintering curves may also differ. Causal comparison requires knowledge of those differences.

INMATEC recommends abrasion-resistant components, including the mold, in its K1010 and K3030 datasheets. The datasheet therefore does not approve a reusable photopolymer mold. Experimental use requires measurement of wear, dimensional drift and contamination; a sacrificial mold avoids accumulating cycles but not wear during filling [9,37].

10. EB1, EB2G and direct printing suspensions

System	What is purchased	Loading and route	Role in the study
3Dresyn EB1 [15]	Powder-free binder.	Up to 60 vol.% powder declared; partial aqueous and thermal removal.	In-house formulation; not ready-to-mold pellets.
3Dresyn EB2G [16]	Binder for glass and silica.	No single loading located; aqueous and thermal fractions.	Glass-specific case; do not assume equivalent use with every metal.
Lithoz [19-20]	Suspensions for direct ceramic printing.	Loading and cycle depend on grade; alumina datum identified in Section 7.	Route comparator against printed mold + injection.
3DCeram [21]	Photopolymerizable suspensions, including CERA-Alumina.	Loading not located in the public page consulted.	Open platform; printing and final cycle require qualification.
Glassomer [22-23]	Solid compounds for injection; liquids for printing/casting.	Exact loading by product not located.	Distinguish service, liquid resin and possible granulate supply.

The EB1 and EB2G pages give mixing at 160 °C and aqueous extraction at 65 °C as reference conditions. The sources consulted do not publish the effective density needed to convert each formulation, the soluble/insoluble split or a universal mass-based recipe. These data must be measured or documented before claiming equivalence to commercial pellets [15-16].

The public designation located for the second binder is **EB2G**, which is used throughout this report. The 10 wt.% binder content is restricted to the preceding 90/10 scenario; it is not a general recommendation for EB1 or EB2G.

Direct printing should not be reduced to “all binder is removed thermally”: investigated formulations include partial aqueous extraction. That does not allow this mechanism to be attributed to all commercial suspensions [32].

10.1. 3Dresyns powder-containing and custom feedstocks

The portfolio also includes powder-containing feedstocks and a custom formulation service [48-51]. These are separate from powder-free EB1/EB2G and from photopolymer suspensions used for direct printing.

Offering	Documented material and route	Loading and comparison limit
CS YSZ1 [49]	YSZ with 3 mol.% Y2O3 and an EB1-based binder. Solid at room temperature; hot injection, aqueous and thermal debinding, then sintering.	Exact powder loading and extractable binder fraction: ND. Supplier-declared route.
MS Ti1 [50]	Titanium with an EB1-based binder. Solid at room temperature; hot injection, aqueous debinding and a thermal stage under argon.	Exact powder loading and extractable binder fraction: ND. Do not infer final properties.
Custom ceramic and metal slurries [51]	Declared formulation and supply service. Examples include alumina, zirconia/YSZ, SiC/SiSiC, Si3N4, hydroxyapatite, 316L, Ti, W-Mo and Co-Cr.	Define the powder, loading, binder and processing specification for each project; listed families are not interchangeable grades.

The custom-formulation service accepts projects for **any customer-specified powder**, subject to compatibility assessment and qualification of the intended process. This service scope was stated by the author on November 8, 2026; the materials listed above are examples. Mold removal, binder removal and, where applicable, sintering must be defined for each formulation.

The supplier states ceramic dispersions up to 65 vol.% and offers custom supply, including cartridges [51]. This is a general formulation capability, not the measured loading of CS YSZ1, MS Ti1 or every customized product.

What changes in the comparison

Purchasing a formulated slurry transfers powder incorporation and formulation work to the supplier; purchasing EB1 leaves that work with the user. Compare delivered feedstock cost per kilogram of contained powder and ultimately per accepted part. The 90/10 bronze scenario and the assumed 40 EUR/kg binder price are not recipes or prices for these complete feedstocks.

For a custom supply, agree grade, powder size distribution, mass and volume loading, rheology, extraction route, residual chemistry, shrinkage and acceptance criteria. Apply the same qualification criteria used for other suppliers of custom feedstocks.

The public product descriptions identify hot-process feedstocks, so the word slurry does not imply an aqueous liquid at room temperature. Commercial statements on density, defect reduction or suitability remain supplier statements unless supported by a defined test and a comparable final-part specification.

11. Comparison of debinding routes

Route	Potential advantage	Penalty or limitation	Required information
Water + thermal	Remove a soluble fraction before heating and open pores.	Swelling, weakening, drying, bath management and powder reaction.	Extractable fraction, wet strength, time to reach the core and residues.
Solvent + thermal	Selectivity for waxes or other components when designed into the system.	Attack on mold or backbone; solvent recovery, drying and equipment.	Compatibility, solubility, bath concentration and binder residue.
Catalytic	Depolymerization of suitable systems such as POM; potential industrial integration.	Equipment, off-gas treatment and chemical compatibility; plain water is not a substitute.	Exact grade, target mass loss and residue; one or more stages as specified.
Direct thermal	Avoids an additional liquid extraction step for the binder.	Higher initial organic content; gradients, internal gas pressure, support and cycle requirements.	TGA/DSC, gases, critical thickness, atmosphere and actual furnace loading.
Thermal with capillary wicking	A porous support can remove molten components from suitable systems.	Contact, cleanliness, contamination and geometric support.	Bed compatibility and shape evolution; do not confuse with evaporation alone.

An aqueous route can reduce organic solvent use, but this alone does not establish a lower overall environmental impact. Heating, water use, drying, emissions, waste treatment and rejected parts must be included. The same caution applies to any claim of energy savings from using an economical printer.

The dimensional scaling of the diffusion equation at constant diffusivity is $t \propto L^2/D$. Only under that assumption does the characteristic time grow with the square of the extraction distance. This is a design guide, not a universal debinding law: swelling, reaction, changing porosity and moving removal fronts may alter the dependence. Thickness and access matter more than mass or build-platform area alone.

Commercial documentary basis: [4-13,15-16,36-38]. Enneti [42] reviews thermal removal and defect formation; its abstract does not validate a specific cycle. The handbooks [39-41] are identified as general background with declared access limitations.

12. Mold removal and debinding are different operations

The sequence must specify what is removed, by which medium, and what supports the part at each stage. Two materials being water-soluble does not guarantee stable simultaneous removal. A mold can swell while the part loses binder and load-bearing capacity.

Architecture	Advantage	Decisive limitation
Reusable metal mold	Stable reference for repeated injection, heat transfer and comparison.	Initial cost and demolding constraints; soluble core if topology requires it.
Reusable photopolymer mold	Rapid insert fabrication and allocation of cost across several cycles.	Measured wear, creep, thermal fatigue, demolding and dimensional drift.
Aqueous-removable sacrificial mold	Geometries that prevent mechanical extraction; removal without conventional mold opening.	Loss of support, swelling, washing time and powder compatibility.
Solvent-removable sacrificial mold	Allows a mold-removal medium different from the binder-extraction medium.	Actual selectivity; retained solvent, attack on organics and cavity cleaning.
Hybrid mold: metal support and printed insert/core	Reduces resin volume and provides support during filling.	Interface design, sealing, differential shrinkage and access for removal medium.

Basso and co-workers describe alkaline mold removal followed by binder extraction with n-heptane: the medium used to remove the mold need not be the binder-extraction medium [29]. This is a useful precedent for designing selectivity, without extrapolating its outcome to every soluble resin.

Removing both mold and binder solely by heating adds the organic mass of the mold to the cycle. Expansion, gas evacuation, contact and contamination must be evaluated. A material that can be burned out for investment casting is not automatically qualified to remain in contact with a green part during debinding.

13. Compatibility matrix requiring resolution

All cells below are conditions to evaluate, not approvals for use. Compatibility depends on grade, geometry, cure state, pressure, temperature and removal medium.

Feedstock	Reusable mold	Aqueous sacrificial mold	Solvent sacrificial mold
Aqueous + thermal	Conditional on filling, wear and demolding.	Mold and binder extraction may overlap: validate loss of support.	Check attack on the backbone; prefer a selective sequence.
Solvent + thermal	Mold is removed before the bath, except for a retained core.	Potential selective mold removal if the feedstock withstands water.	Risk of simultaneous extraction or swelling: validate selectivity.
Catalytic POM; finishing by grade	Industrial baseline; validate the polymer mold.	Removing the mold before catalytic debinding may separate the operations.	Confirm resistance and cleanliness before the catalytic reactor.
Direct thermal	No binder bath; verify support during heating.	The bath may still affect powder, additives and green strength.	A solvent-free debinding route does not establish feedstock stability in a solvent.
Photopolymerizable suspension	Only if a curing mechanism exists inside the mold.	Injection and cooling are insufficient; curing and compatibility are required.	Not equivalent to thermoplastic MIM/CIM pellets.
Aqueous casting/gel suspension	A nonporous mold requires an appropriate consolidation mechanism.	Suspension water may attack a water-soluble mold from the filling stage.	Possible alternative if chemically compatible and consolidation occurs.

Photopolymerizable suspensions add a prerequisite: the interior must consolidate. Exposing the outside of an opaque mold does not demonstrate uniform curing of its contents. With an aqueous suspension, a water-soluble mold may be incompatible from initial contact, even if useful in another hot-injection route.

A datasheet for a reusable or sacrificial resin describes a material; it does not certify every cell of this matrix. Low equipment cost does not determine compatibility either: the verifiable criterion is the stability and reproducibility of the mold produced with that equipment.

14. Metals: priorities and limits of transfer

Family	Interest in extending the study	Priority risk or quality variable	Comparator
316L and 17-4PH	Starting point with several commercial binder families.	Final composition, pores, residual carbon, heat treatment and strength; do not interchange the two steels.	Same feedstock in a metal mold.
Cu and Cu-Sn	Continuity with the earlier cost analysis; potential internal geometries.	Oxygen, porosity, shrinkage, actual composition and leak tightness if required.	Casting or machining of the same alloy to the same specification.
Cu-Al / Cu-Al-Ni-Fe	Technically relevant extension, but not equivalent to Cu-Sn or pure copper.	Powder surface condition, phases, atmosphere and corrosion/erosion behavior.	The actual casting alloy being replaced.
Ti and alloys	High-value case for geometry and reduced machining.	Control of interstitials and contamination throughout; dedicated furnaces and handling.	Qualified route for the same material, not bronze.
WC-Co and dense metals	Show that a low binder mass fraction may still be a high volume fraction.	Chemical balance, phases, abrasiveness and wear; do not apply a steel cycle.	Equivalent conventional material and required finish.

Start with a commercial steel feedstock-mold pair and with alumina to separate tooling questions from development of a difficult alloy. Cu-Sn remains an economic and in-house formulation case; Cu-Al requires additional metallurgical verification before assigning a production yield.

The AMP portfolio includes various alloys and materials in its datasheets [6-7]. This justifies exploring additional families, but does not replace the datasheet for the selected grade. The table proposes technical control variables; these are not comparative results already obtained.

The 0.5, 2 and 10 kg masses in the economic scenario are extrapolations without validation of manufacturability, debinding or sintering. Mass, transport thickness and geometry must be evaluated separately; build area does not qualify the part.

15. Ceramics and glass: extending without conflating functions

Family	Role in the comparison	Proposed main control
Alumina	First CIM reference; several commercial routes and loading measurements.	Relative density, defects, strength scatter, roughness and mold wear.
Zirconia	Second structural case; comparison of density and binder system.	Phases, shrinkage, distortion, defects and strength in the final state.
Fused silica	Case for EB2G and comparison with glass solutions.	Purity, bubbles, transmission and optical roughness where relevant; density does not substitute for transparency.
AlN	Boundary case for aqueous routes.	Powder-water reactivity, surface treatment, residues and thermal properties.
Si_3N_4 / SiAlON and other non-oxides	Extension after a baseline route has been stabilized.	Exact chemistry, additives and atmosphere; do not use an alumina cycle by analogy.
$BaTiO_3$ and BNT-BT	Documented functional examples in printed molds.	Phase, density, defects and functional response; strength or porosity alone is insufficient.

Oliveira and co-workers show that protection against hydrolysis and dispersion of AlN depend on its surface treatment. Water is therefore not a universally harmless route for every powder. The result does not require excluding all AlN either: the grade must be specified and the medium validated [33].

Didilis studies zirconia, alumina and two piezoelectric ceramics, with dissolution difficulties and defects dependent on geometry and flow. This is a direct precedent for extending the approach to multiple ceramics, so that extension alone is not a first [28].

The commercial glass reference distinguishes solid and liquid compounds [22-23]. A powder-binder injection formulation does not automatically establish optical quality. Nor are the properties of an LCM suspension attributed to a printed mold: these are different manufacturing routes [19].

16. Quality: what must be preserved when changing process

Criterion	Potential benefit	Potential disadvantage	Decision metric
Geometry	Complex cavities and fewer components.	Incomplete filling, weld lines, warpage and amplification of mold errors.	Dimensions by stage and deviation from CAD and control.
Surface	Detail replication and reduced machining allowance.	Print stair-stepping, uneven exposure, wear or gate marks.	Ra/Sa in defined areas and required machining allowance.
Internal defects	Reproducible process if mixture and flow are controlled.	Segregation, pores, delamination or cracking during removal and heating.	Sections or tomography with stated resolution.
Final state	Potential to tailor composition and microstructure.	Residues, contamination, oxidation or undesired phase.	Chemistry and phases; density with open/closed porosity.
Mechanical performance	Properties adjustable through material and cycle.	Brittleness, scatter or anisotropy not detected by density.	Strength, strain and toughness as required; not interchangeable terms.
Function and service life	Integration of channels and functions.	Leaks, corrosion, erosion, fatigue or loss of functional properties.	Testing of the service requirement in addition to coupons.

Two questions should be compared: first, the same feedstock in different molds; then, processes optimized for the same final specification. The first helps attribute causes. The second is relevant to purchasing and industrial substitution. Density and microstructure should be measured when they help explain the result; forcing them to be equal at the design stage changes the question if they are consequences of the process being compared.

Absence of a statistically significant difference is not treated as equivalence. Acceptance limits, measurement uncertainty and sample sizes must be set according to risk and variability. Successfully printing the mold does not demonstrate that the final part meets those limits.

17. Economical printers: qualification criteria

SLA, DLP and LCD can produce useful molds. This study evaluates the achieved process without inferring its quality from purchase price. Build areas of 30 × 16 cm, 33 × 18.5 cm and 52.7 × 29.6 cm are accepted as project constraints supplied by the sponsor; they are not attributed here to specific models or current offers.

Variable	Why it affects the result	Proposed check
Irradiance and spectrum	Change curing, geometry and mold properties.	Irradiance map and repeatability using a sensor suitable for the wavelength.
Temperature and time	Affect viscosity, curing, relaxation and dimensional stability.	Record resin, ambient conditions, post-curing and condition before injection.
Optics and position	Nominal pixel size or spot diameter is not cavity accuracy.	Patterns at the center, edges and corners; different part orientations.
Washing and post-curing	May change dimensions, surface and strength, especially in channels.	Fixed procedure and verification of internal cleanliness.
Mold construction	Thickness, supports, gates and frame change pressure response.	Validate the complete mold under the actual pressure-temperature history.

IM-HDT and IM-HDT-WS represent different architectures: reusable and aqueous-removable sacrificial molds. The public IM-HDT-WS page states HDT <160 °C at 0.45 MPa. That inequality is neither a guaranteed minimum resistance nor an allowable injection pressure. The mold response must be checked in its actual geometry and condition [17-18].

As an ideal estimate, at 60 vol.% powder and a final relative density of 0.98, the linear scale factor is (0.98/0.60)^(1/3) = 1.178. Walls, gates and supports must be added to that oversizing. Usable build area alone does not determine the final manufacturable part size.

The estimate assumes conserved inorganic mass, isotropic shrinkage and compatible densities; it does not replace measured compensation along each axis. Formlabs offers guides to printed molds, but use in polymer injection molding does not automatically qualify an abrasive MIM/CIM feedstock [35].

18. Costs: normalize before comparing prices

For a purchased feedstock priced at Pf with powder mass fraction w_p, the ideal material cost per kilogram of contained powder is Pf/w_p. For in-house compounding, raw-material cost per kilogram of powder is $P_p + [(1 - w_p)/w_p]P_β$. These balances precede losses, manufacturing and quality control.

Item	Commercial feedstock	Powder + EB1 / EB2G or another binder
Comparable price	Delivered EUR/kg of mixture, specifying grade, lot, quantity and terms.	Separate powder and binder EUR/kg under the same delivery terms.
Preparation	Partly included in the product; confirm conditioning or drying.	Mixing, pelletizing, dispersion, homogeneity and lot analysis.
Development	Adjustment to mold, machine and part; qualification.	Also formulation development and stability.
Risk and supply	Traceability, consistency, support and minimum orders.	Flexibility, own quality control and procurement of both components.

At 90.0 wt.% powder and a binder price of 40.00 EUR/kg, binder contributes **4.44 EUR per kilogram of powder**, before consumption allowances. At 60 vol.% powder, it contributes 3.03 EUR/kg of Cu-Sn, 6.75 EUR/kg of alumina and 12.12 EUR/kg of fused silica. These are not commercial feedstock prices.

A set of current quotations comparable by grade and volume has not been obtained for all manufacturers. Fictitious prices are therefore not assigned to Catamold, polyMIM, INMATEC or Lithoz. Monetary scenarios remain separate from commercial data and are normalized to inorganic content and required quality.

Mold cost includes resin, supports, losses, printing, cleaning, post-curing, assembly and inspection. For a reusable mold it is allocated across verified useful cycles, not an assumed service life. For a sacrificial mold, removal and bath treatment are added. Printer depreciation may be small compared with labor, furnace operation and rejection.

19. Stage-based model and the cost of rejected parts

Let c_i be the incremental cost per part entering stage i, and q_i the fraction passing that stage. With no rework or re-entry, variable cost per accepted part is:

$C_{variable} = \Sigma_i c_i / (q_i \times q_{i+1} \times \ldots \times q_k)$
C total = C variable + F / N accepted
F represents development and tooling not already included in stage costs. Recovery credits must be assigned where they arise, at their actual net value.

Illustrative example	Early rejection	Final-stage rejection
Entry costs in four stages	10 + 20 + 30 + 5 EUR	10 + 20 + 30 + 5 EUR
Conditional yields	0.90; 1; 1; 1	1; 1; 1; 0.90
Overall yield	90 %	90 %
Cost per accepted part	66.11 EUR	72.22 EUR

Both cases have the same overall yield, but late rejection consumes more resources. An industrial comparison must record when a defect arises and when it is detected. Dividing total cost by overall yield is correct only with a consistent allocation of the costs actually incurred by rejected parts.

Variables that may reverse the decision

Useful furnace loading and acceptance yield may matter more than an additional resin discount. Avoided machining, the number of variants, molds per print and reusable mold life may also dominate. Outsourcing must be compared with avoidable costs: not every accounting cost of an existing facility disappears when the route changes.

Heating, maintenance, atmosphere, consumables, labor, inspection and furnace utilization are included, not only electricity. Machining savings are not counted twice if already included in the finishing line. Furnace cycles are allocated using actual utilization and productivity, not nominal empty volume.

20. Bronze: economic screening and scale limitations

A **generic scenario retaining the project sponsor assumptions** is used. The numerical table is not attributed to the earlier study [1]. Its starting point is archived in version 1.0. These are not current quotations or manufacturing results. Costs are expressed per accepted part.

Final mass	Cast Cu-Sn	Cu-Sn powder 24.16 EUR/kg	Cu-Sn powder 60.00 EUR/kg	Cast / powder Cu-Al 60.00 EUR/kg
0.5 kg	77.93	91.05	113.85	76.47 / 125.78
2.0 kg	159.07	225.42	316.62	153.27 / 346.68
10.0 kg	483.78	832.87	1,288.88	454.76 / 1,409.76

Recurring costs, excluding fixed costs. Binder: 40.00 EUR/kg; resin: 40.00 EUR/kg. Powder-route yield from conforming mold: 85.0 %. Powder prices do not establish MIM suitability or constitute feedstock quotations.

Final mass	Cu-Sn threshold EUR/kg powder	Cu-Al threshold EUR/kg powder
0.5 kg	3.53	-17.50
2.0 kg	-1.91	-16.01
10.0 kg	-3.28	-15.06

The threshold equalizes recurring costs while holding everything else constant. A negative value means that even free powder would not match casting costs in that case. Each row shows the scope of this negative result; it is neither a physical prohibition nor a universal conclusion.

Durofer describes typical masses around 1-100 g and allows heavier parts [46]; ARC reports up to 500 g in the MPIF directory [47]. Typical supplier ranges are not universal physical maxima. The masses in this table remain unqualified for bronze, EB1 and a printed mold; 2 and 10 kg are extrapolations particularly far from usual practice.

20.1. Boundaries, consumption and cost assumptions

Shared assumption	Value
Cu-Sn / Cu-Al metal price basis	18.55 / 16.00 EUR/kg
Binder / mold resin	40.00 / 40.00 EUR/kg
Preparation per kg of mixture	2.00 EUR/kg
Baseline thermal cycle / Cu-Al factor	400.00 EUR / 1.5
Casting yield	95.0 %
Conforming mold per print attempt	95.0 %
Accepted part from conforming mold	85.0 %
Combined yield from print attempt	80.75 %
Resin / mixture allowances on nominal quantity	10.0 % / 5.0 %
Casting / powder-route machining allowance	10.0 % / 3.0 %

The cost of obtaining a conforming mold is already divided by print yield. The yield from that mold to an accepted part is then applied. These are successive boundaries, not two estimates of the same overall yield.

Consumption allowances multiply nominal consumption by (1 + allowance). They are not input loss fractions, which would require division by (1 - loss). The original balances and recovery credits are retained; physical recovery and scrap price are different variables.

The JSON and dictionary identify each per-part, per-print and per-furnace cost. Fixed costs are separated into dev for the powder route and fixed_casting for casting. Zero casting fixed cost means costs already amortized or not avoidable in this decision, not that patterns or setup historically cost nothing.

calculos.py allows the documented economic inputs to be varied. The report generator takes numerical statements and labels from resultados.json. It does not predict furnace capacity, yield, defects or whole cycles per batch. Changing geometry or process architecture requires reassessing assumptions, not merely changing a cell.

21. Sensitivity: yield and furnace utilization

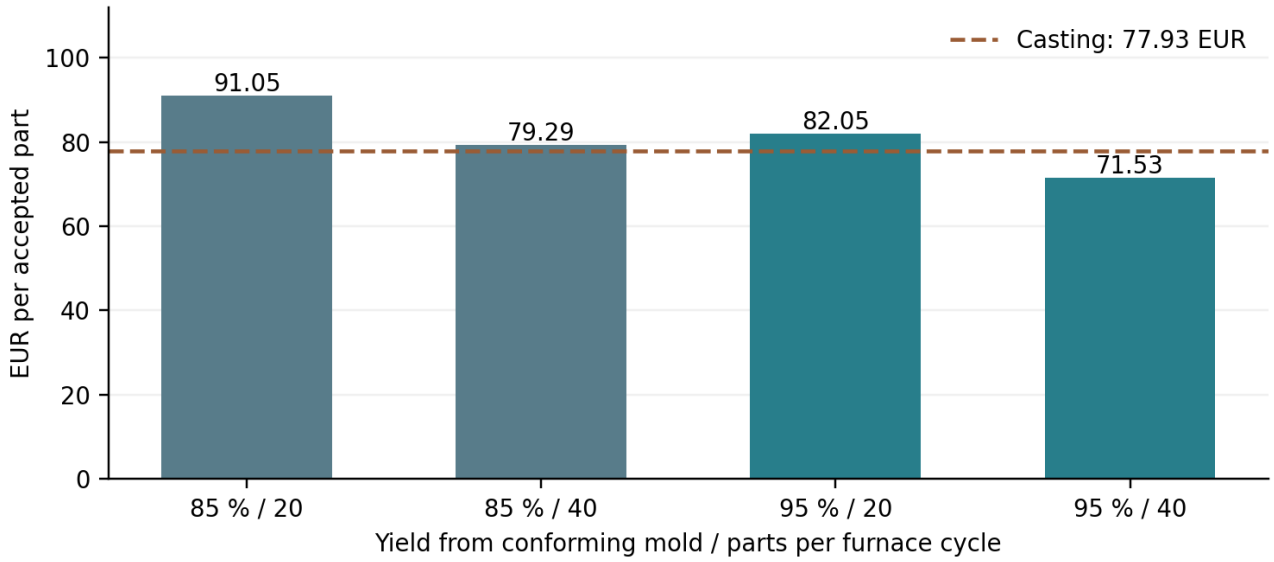

Figure 2. Hypothetical Cu-Sn case, 0.5 kg. Powder: 24.16 EUR/kg; binder: 40.00; resin: 40.00 EUR/kg. Yield from conforming mold and furnace utilization vary; baseline cycle cost is 400.00 EUR.

The Section 20 base case costs 91.05 EUR by the powder route and 77.93 EUR by casting. The selected sensitivity case, with 95.0 % yield from conforming mold and 40 parts per furnace cycle, costs 71.53 EUR by the powder route; the casting reference is 77.93 EUR.

The recurring cost difference (casting minus powder route) is 6.40 EUR/part. A positive sign favors the powder route; a negative sign favors casting. Total costs also depend on the fixed costs of both alternatives.

The powder price threshold in that case is 35.40 EUR/kg. This is neither an obtained quotation nor an industrial forecast. Utilization and yield must be maintained at the same quality; doubling the load requires checking geometry, gas circulation and uniformity.

Other materials require their own grade, loading, delivered price, cycle, capacity, recovery and specifications. Bronze prices, scrap recovery and thermal factors are not transferred to steel or ceramics.

21.1. Fixed costs of both alternatives

C casting = c casting + F casting / N
C powder route = c powder route + F powder route / N
The powder route is no more expensive if N × (c casting - c powder route) ≥ F powder route - F casting.

The table uses the selected sensitivity case from Figure 2: 95 % yield from conforming mold and 40 parts per furnace cycle. With F powder route = 9,000 EUR and F casting = 0 EUR, totals at N = 1,000 are 80.53 EUR/part for the powder route and 77.93 EUR/part for casting.

F casting	Casting total EUR/part	Powder-route total EUR/part	Powder route no more expensive
0 EUR	77.93	80.53	From 1,407 parts
3,000 EUR	80.93	80.53	From 938 parts
9,000 EUR	86.93	80.53	All positive N

The fixed costs in the table are assumptions, not quotations. With the configured fixed costs, the powder route is no more expensive: from 1,407 parts. Casting fixed cost equalizing the two routes at N = 1,000 is 2,601.00 EUR. If that result were negative, the powder route would already cost less at that N even with zero casting fixed cost.

In the Section 20 base case, with 85 % yield from conforming mold and 20 parts per furnace cycle, the powder route costs 13.13 EUR/part more in recurring costs. There is no high-volume payback. To equalize costs at N = 1,000, casting would require 22,125.94 EUR in its own fixed costs.

With positive recurring savings and higher powder-route fixed cost, the integer threshold is the upward rounding of (F powder route - F casting)/(c casting - c powder route). Without those savings there is no high-volume payback; small batches may benefit if powder-route fixed costs are lower.

The model uses average utilization without whole furnace cycles per batch, and holds yield, capacity and quality constant. Fixed costs must be avoidable in the decision; an amortized investment must not be charged again to change the sign of the comparison.

22. Proposed evaluation program

Stage	Design	Required outcome
1. Identify materials	Select grade and lot; record powder, loading, binder, removal route and datasheet.	Comparable datasheet and delivered price, or explicit ND.
2. Qualify formulation	TGA/DSC, density, homogeneity and rheology within the working window.	Processable loading and stability, not just a maximum percentage.
3. Qualify mold	Same CAD, washing and post-curing; measure before and after filling.	Pressure-temperature-time window and service life if reusable.
4. Resolve removal	Mold coupons, green part and assembly; defined media and times.	Selectivity, integrity and residue, with each mass loss identified.
5. Verify final part	Independent lots, recorded furnace positions and equivalent finishing.	Dimensions, defects, chemistry and functional requirement.
6. Measure economics	Actual times, consumption, utilization and rejection detected by stage.	Cost per accepted part and decision sensitivity.

Recommended initial matrix: a commercial alumina with an aqueous route, an alumina with a solvent or catalytic route, and a commercial 316L. In each case, compare a reference mold with a reusable printed mold and, where topology justifies it, a sacrificial mold. Do not start with a large, complex part combining formulation, mold and sintering uncertainties.

EB1 is included as an identified in-house formulation with a selected powder, without assuming the same loading as commercial pellets. EB2G is included in a separate silica or glass case. Binder comparisons require the powder to be held constant; optimized-route comparisons require the final specification to be held constant. These are different experimental objectives.

No universal specimen count is prescribed. First estimate between-lot and between-part variability; then size the comparison for the relevant difference or equivalence margin. The detailed aqueous protocol already developed in [1] can be reused without presenting it again as a new contribution.

23. Information gaps and scope of conclusions

Minimum information for comparable quotations and samples

Request grade and revision; powder and composition; d10/d50/d90, morphology and specific surface area where relevant; mass and volume loading; conversion densities; vehicle and extractable fraction; mass basis and expected residue; rheology; injection conditions; debinding and sintering cycle; shelf life; permitted reprocessing; traceability; minimum order quantities and delivered prices by quantity. No request was sent during this review.

For molds: resin version, printer and wavelength, calibration, orientation, thickness, support, washing, post-curing, cavity pressure, temperature, contact time, removal medium and service life. These data are needed for a verifiable comparison between an economical printer and a more expensive one.

Contribution and further research

Critical documentary review and comparative framework. The study links heterogeneous commercial data to tooling compatibility, quality and reproducible economics. The evidence does not establish universal superiority of one brand of mold, EB1/EB2G or a debinding route.

The conclusions are bounded by the stated source-access and supply limitations. Further experimental work should measure compatibility windows and quantify how actual rejection rates and final-part quality change the cost comparison.

Declaration of interest

Juan Segurola is affiliated with 3Dresyns. Its materials are included for their relevance to tooling and formulation, applying the same distinction between commercial statements, independent measurements and assumptions as for other suppliers.

The supporting files contain source registers, datasets and reproducible calculations. Conclusions are limited to the sources and assumptions stated. © 2026 Juan Segurola. All rights reserved for the original content; rights to cited sources remain with their respective holders.

References and extent of access

Commercial references identify supplier statements. Scientific references are used within the material and protocol studied. “Accessible” does not mean reproduced in full in this report. Locators and access levels are supplied in datos/fuentes.csv; English access descriptions are provided in datos/references_en.json.

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