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Beyond Nominal G: A Critical Review of Scale-Up Principles, Hydrodynamics, and Industrial Translation of Enhanced Gravity Concentrators in Mineral Processing

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Abstract

Enhanced gravity concentrators (EGCs) extend density-based separation into fine and ultrafine particle-size ranges by imposing centrifugal acceleration, but industrial scale-up often reduces to matching a nominal G value. That simplification is inadequate because geometrically different or differently sized machines operating at the same nominal G can exhibit different fluid-film or bed thicknesses, velocity and pressure fields, residence-time distributions, solids fluxes, particle trajectories, retention states, concentrate capacities, and circuit duties. This critical review examines the engineering basis for transferring EGC performance from laboratory to pilot and industrial scales, focusing on Knelson concentrators, Falcon SB, C, and UF configurations, and Multi-Gravity Separators. A curated evidence base of 97 publications from 2015 to September 2026 is interpreted through three evidence classes: direct EGC mechanism or performance evidence, bench-to-pilot/plant and circuit evidence, and transferable scale-up analogies. The review distinguishes fixed-geometry optimization from inter-scale transfer and evaluates local centrifugal acceleration, Reynolds and particle Reynolds numbers, Stokes number, a centrifugal flow-inertia ratio, migration-to-residence similarity, and normalized solids capacity as candidate diagnostics rather than universal scale-up laws. The synthesis shows that force field, hydrodynamics, particle properties and liberation, transient bed/film behavior, solids loading and capacity, and circuit context jointly control scale-dependent performance. Plant evidence further shows that availability, classification, recycle, feed variability, and downstream concentrate treatment can dominate deviations between predicted and realized recovery. Accordingly, reliable EGC scale-up requires preserving or deliberately re-optimizing the dominant controlling

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mechanisms and similarity criteria for each architecture and duty, followed by independent performance validation at industrial scale.

Keywords: Enhanced gravity concentration; Scale-up; Dynamic similarity; Hydrodynamics; Centrifugal separation; Fine-particle beneficiation.

Highlights

- Nominal G characterizes centrifugal intensity but is insufficient as a stand-alone scale-up criterion.
- Force field, hydrodynamics, particle dynamics, bed/film behavior, solids loading and capacity, and circuit context jointly govern scale-dependent performance.
- Knelson, Falcon SB/C/UF, and MGS architectures require different architecture-specific similarity criteria and validation strategies.
- Reliable bench-to-plant transfer requires independent validation and circuit closure, including recycle, availability, and downstream recovery.

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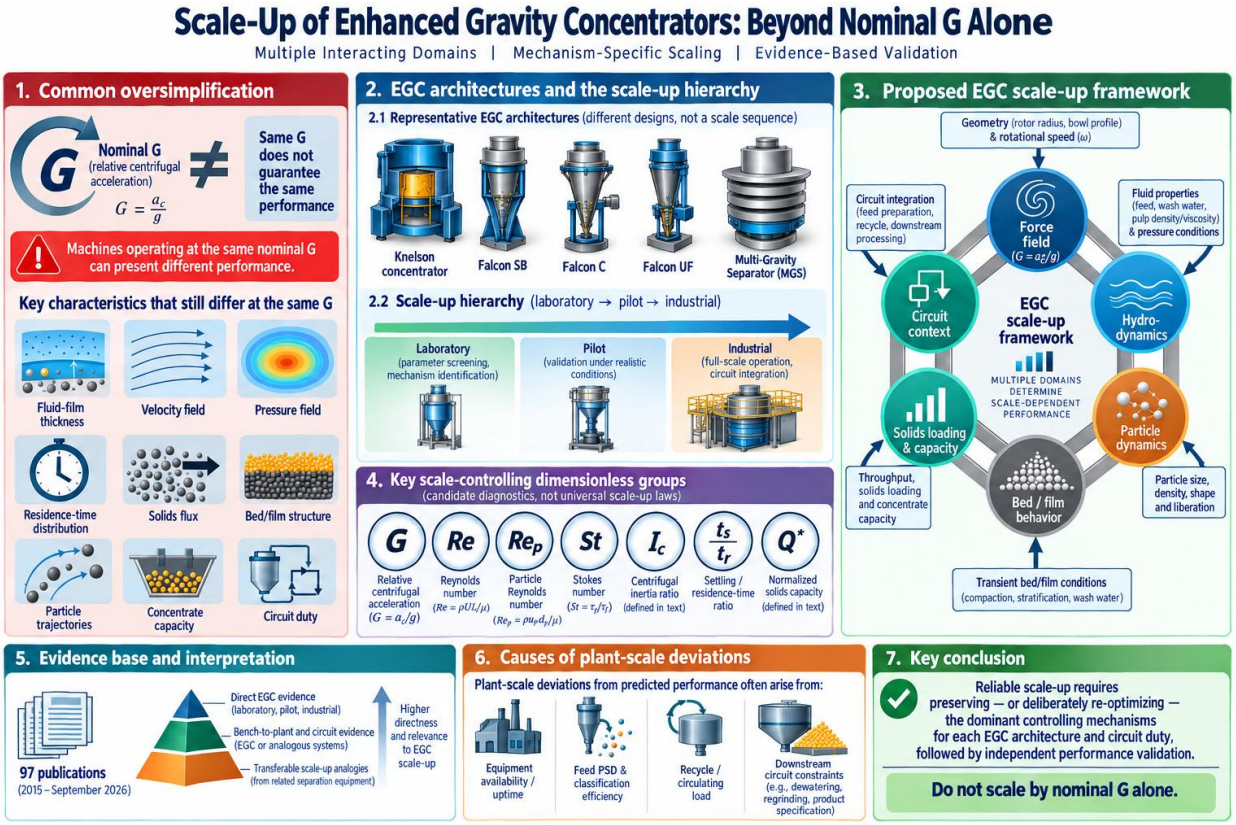
Graphical abstract



1. Introduction

Fine and ultrafine mineral beneficiation increasingly requires separators that exploit density differences at sizes where conventional gravity devices lose efficiency. Enhanced gravity concentration addresses this limitation by imposing centrifugal acceleration and, depending on machine architecture, combining it with fluidization, thin-film flow, retention zones, continuous discharge, or oscillatory washing. Reviews identify Knelson, Falcon, and Multi-Gravity Separator (MGS) devices as important approaches for extending gravity separation beyond the practical operating domains of jigs, spirals, and tables (Das & Sarkar, 2018; Nayak et al., 2021; Nzeh et al.,

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2023; Phengsaart et al., 2023). Their appeal extends beyond concentrate production: EGCs can preconcentrate ore, reject gangue before energy-intensive downstream stages, recover liberated value from circulating loads, and treat secondary resources and tailings with limited reagent demand (Ramudzwagi et al., 2020; Surimbayev et al., 2025).

The engineering difficulty begins when a successful laboratory test is transferred to a larger machine. Centrifugal intensity is commonly summarized by the dimensionless ratio $G = \omega^2 r/g$, but equal nominal G does not imply equal dynamic states. Changing bowl or drum radius while preserving G requires a corresponding change in angular velocity, and that change does not preserve peripheral velocity, fluid-film or bed thickness, residence-time distribution, turbulence, particle relaxation, specific solids flux, fluidization or wash-water state, retention capacity, or circuit coupling. Mechanistic Knelson studies show that water velocity, pressure distribution, particle–particle interactions, feed density, and retention-zone behavior respond to geometry and operation through coupled local fields (Chen, Yang, Tong, Lin, et al., 2020; Chen, Yang, Tong, Liu, et al., 2020; Fatahi & Farzanegan, 2017, 2018, 2019; Frigger et al., 2024; Yuan et al., 2024). Falcon studies likewise demonstrate sensitivity to fluid velocity, particle size and density, film behavior, treatment time, and resuspension, particularly in ultrafine operation (Das, Kundu, et al., 2023; Das, Tan, et al., 2023; Dehaine et al., 2019; Singh, Kishore, et al., 2020; Singh, Sahu, Chalavadi, Swain, et al., 2021).

Practically, machines operating at the same nominal G may occupy different hydrodynamic, particle-dynamic, bed/film, and capacity regimes. In Falcon UF treatment of ultrafine scheelite tailings, feed configuration and particle-size distribution can outweigh moderate changes in G within the tested range, whereas MGS optimization reveals opposing grade and recovery responses to drum speed, wash water, and slope (Bru et al., 2026; Çerik & Şen, 2026). These observations are consistent with separation being controlled by coupled force, transport, retention, loading, and discharge mechanisms. The more defensible scale-up question is therefore not simply “what G

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should be preserved?" but "which similarity relationships control the target separation mechanism, and which must be preserved or deliberately re-optimized at the larger scale?"

This review develops that question into a mechanism-based engineering framework. It classifies EGC architectures and operating domains, examines why nominal G is insufficient, distinguishes fixed-scale optimization from inter-scale transfer, evaluates candidate dimensionless and mechanistic diagnostics, compares equipment-specific constraints, and assesses laboratory, pilot, circuit, and industrial evidence. The synthesis culminates in an EGC Scale-Up Similarity Framework with six interacting domains: force field, hydrodynamics, particle dynamics, bed/film behavior, solids loading and capacity, and circuit context. The framework is intended to make scale-up assumptions explicit and auditable. It is an author-developed conceptual framework, not a universal correlation, and it has not yet been prospectively validated as a predictive scale-up model. Architecture-specific descriptors therefore supplement the six common domains for physically different separator designs.

2. Review Methodology and Evidence Classification

2.1 Scope and review design

This manuscript is a structured critical review, not a systematic review or meta-analysis. The final corpus contains 97 publications dated from 2015 to September 2026, including 35 publications from 2015–2019 and 62 from 2020–2026. The corpus includes experimental studies, numerical and data-driven models, reviews, flowsheet investigations, plant-design or plant-operation studies, and transferable scale-up analogies. The source corpus was curated before the present synthesis and the original database-by-database retrieval log was not retained; consequently, the review does not claim PRISMA-level exhaustiveness and does not retrospectively assign each paper to a database that cannot be documented. The final literature update for this revision was completed on 27 September 2026. The review instead treats the corpus as a structured evidence base for testing a specific engineering proposition: EGC scale-up must

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preserve the dominant mechanism set, not nominal G alone. Three evidence classes are retained throughout: (A) direct EGC mechanism or performance evidence; (B) bench-to-pilot/plant, circuit, or predictive evidence; and (C) transferable scale-up concepts from rotating drums, cyclones, residence-time theory, dimensional analysis, and multidimensional separation functions. Class C evidence is used to motivate hypotheses and diagnostic criteria and is not treated as direct validation of EGC scale-up behavior.

Search and evidence-selection procedure. The final update used combinations of the principal blocks "enhanced gravity concentrator" OR Knelson OR Falcon OR "Multi-Gravity Separator" OR MGS with scale-up terms (scale-up, similarity, pilot, plant, industrial, geometry, hydrodynamics, residence time, capacity, fluidization, film, bed, CFD, DEM, and validation). Citation chaining from key reviews, mechanism papers, and industrial case studies was used to identify additional eligible studies. English-language journal articles, reviews, theses, and technically documented industrial studies were eligible when they contributed directly to EGC mechanism/performance, bench-to-pilot/plant transfer, circuit behavior, modeling transferability, or a clearly labeled transferable scale-up analogy. Studies were excluded when they lacked sufficient technical detail to interpret the scale link, duplicated an already retained report, or addressed conventional gravity separation without a transferable similarity argument. Because the original source-by-source database provenance was not preserved, database coverage is reported only where recoverable from the retained records rather than inferred retrospectively.

2.2 Critical appraisal and synthesis criteria

Each study was interpreted against five questions: (1) Which machine architecture and separation mechanism were investigated? (2) Which geometric, hydrodynamic, particle, feed, and operating variables were reported? (3) Did the study optimize one machine at one scale or compare performance across scales? (4) Were size-by-size, mineralogical, residence-time, or circuit effects resolved, or were only bulk grade and recovery reported? and (5) Was the model or operating rule

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validated outside its calibration domain? No numerical quality score was imposed because the corpus spans heterogeneous experimental and modeling designs. Evidentiary weight was instead assigned qualitatively from the directness of the scale link, completeness of reported variables, mechanistic interpretability, and independence of validation. This distinction is essential because a high-quality response-surface or machine-learning fit at laboratory scale can identify local operating sensitivities without establishing geometric or dynamic similarity. Study-level classification fields used during this revision were reference, architecture, feed, scale, evidence class, direct-versus-analog status, principal variables, validation domain, main scale-up implication, and principal limitation. Because the original curation did not retain all of these fields for every paper, a fully populated 97-study supplementary matrix is not claimed where information could not be recovered reliably.

2.3 Evidence coverage, thematic breadth, and limitations

The corpus is deliberately broad across commodities and feed types because a credible scale-up framework must be tested against different mineralogical and circuit contexts. Knelson applications include rare-earth tailings, clay-rich ores, chromite, copper–cobalt tailings, fine coal, contaminated sediments, and gold circuits (Abaka-Wood et al., 2019; Basnayaka et al., 2020; Go et al., 2015; Katwika et al., 2019; Ma, Wei, Zhu, Pei, et al., 2021; Oney et al., 2020; Rajala, 2021; Samanli & Osmanli, 2023). Falcon studies span coking coal, bentonite, chromite, phosphate, scheelite, rare-earth minerals, tantalum–niobium ores, copper ores, and polymetallic systems (Andavarapu et al., 2022; Freire et al., 2019; Hassan et al., 2025; Ibrahim et al., 2026; Norgren & Anderson, 2021a, 2021b; Özgen, 2017; Zhang et al., 2019; Zhang et al., 2022). MGS evidence covers iron ore, coal, laterite, pyrite-rich polymetallic material, and colemanite (Andavarapu et al., 2023; Chaurasia & Nikkam, 2017a, 2017b, 2017c; Chaurasia et al., 2018; Eljoudiani et al., 2025, 2026; Rao et al., 2017; Tok et al., 2025).

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Flowsheet and mineralogical studies provide additional evidence on liberation and circuit context, including rare-earth and rare-metal beneficiation, kaolin fines, lithium granites, other complex feeds, centrifugal rejection of talc, and automated-mineralogy interpretation of liberation constraints (Filippov et al., 2016; Jordens, Marion, Langlois, Grammatikopoulos, Rowson, et al., 2016; Jordens, Marion, Langlois, Grammatikopoulos, Sheridan, et al., 2016; Klein et al., 2016; Korbel et al., 2025; Marion et al., 2018; Pereira, 2026). Complementary analogies address scale-up of granular flow in rotating drums, cyclone similarity, residence-time distributions, and multidimensional separation functions (He et al., 2024; Herman et al., 2022; Misiulia et al., 2024; Pandey et al., 2022; Rodrigues, 2021; Schach et al., 2025; Xu et al., 2024). This breadth improves mechanistic coverage but also increases heterogeneity; accordingly, cross-commodity analogies identify transferable variables rather than infer universal numerical coefficients.

3. Enhanced Gravity Concentration: Technologies, Architectures, and Operating Domains

Table 1 summarizes the EGC architectures considered in this review and identifies variables most likely to alter the controlling separation mechanism during scale-up. The taxonomy is functional rather than merely descriptive: fluidized retention beds, stratification and retention zones, continuously discharged flowing films, high-G ultrafine films, and inclined oscillating drums all generate enhanced gravity, but they impose different hydrodynamic boundary conditions, residence histories, bed/film states, and capacity constraints.

Table 1. *Taxonomy of enhanced-gravity concentrators and scale-up-relevant operating domains*

Architecture	Dominant mechanism	Typical feed/domain	Scale-up-sensitive variables
Knelson batch/semi-batch	Centrifugal stratification in a fluidized riffle/retention bed	Free or partly liberated dense particles; especially free gold and other dense valuable minerals; selected sulfide, REE, and coal duties	Bowl/riffle geometry, G(r), superficial fluidization-water velocity, specific solids loading, cycle time, retained mass

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Architecture	Dominant mechanism	Typical feed/domain	Scale-up-sensitive variables
Knelson CVD/continuous	Centrifugal retention with controlled continuous concentrate discharge	Continuous or high-mass-pull duties; circulating-load treatment	Discharge setting, specific solids flux, retention/discharge capacity, feed density, circuit recycle
Falcon SB	Smooth stratification zone followed by a fluidized retention zone; semi-batch discharge	Liberated fine dense particles; semi-batch concentrate recovery	Retention-zone loading, fluidization-water rate, cycle time, specific feed flux, G(r), slurry rheology
Falcon C	Flowing-film separation with continuous concentrate discharge	Continuous upgrading or scavenging of fine dense particles	Film thickness/shear, specific solids flux, mass pull/discharge rate, G(r), bowl geometry
Falcon UF	High-G flowing film with a smooth retention zone; semi-batch ultrafine duty	Fine to ultrafine liberated minerals; feed-dependent operating range	Feed PSD, film thickness/shear, retention-zone loading, cycle time, resuspension, solids concentration
MGS	Stratified flowing layer on an inclined rotating drum with oscillation, wash water, and dense-layer transport	Primarily fine-particle separation where selective washing is important	Drum speed, tilt, oscillation amplitude/frequency, wash-water rate, feed solids flux/pulp density, RTD

Note. Operating ranges vary by model and feed; the table emphasizes mechanisms and scale-up variables rather than manufacturer-specific nominal capacities. CVD = continuous variable discharge; MGS = Multi-Gravity Separator; PSD = particle-size distribution; REE = rare-earth elements. Original synthesis based on Chen, Yang, Tong, Niu, et al. (2020), Farajzadeh and Chehreh Chelgani (2022), Nayak et al. (2021), and the MGS studies reviewed herein.

3.1 Knelson concentrators

Knelson concentrators use a rotating conical bowl in which centrifugal acceleration drives denser particles toward retention regions while fluidization water, where used, limits compaction and promotes selective rearrangement. In batch and semi-batch duty, separation therefore reflects a balance among centrifugal migration, interparticle contacts, fluid drag, riffle or ring geometry,

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solids loading, and finite retention capacity; continuous-discharge variants add an explicit discharge-capacity constraint. Mechanistic and review studies show that the bowl should not be treated as a spatially uniform "G field"; radial position, local pressure and velocity, fluidization conditions, and retained mass alter the forces and trajectories experienced by particles (Chen, Yang, Tong, Liu, et al., 2020; Chen, Yang, Tong, Niu, et al., 2020; Chen et al., 2026). Ring-by-ring analyses further show that bed filling and retention capacity are integral to the separation mechanism rather than secondary operating details (Chen, Yang, Tong, Lin, et al., 2020; Ghaffari & Farzanegan, 2017a, 2017b, 2018).

The Knelson literature includes substantial numerical and data-driven work. DEM has reproduced sensitivities to feed mass, particle density, size distribution, feed rate, G, and cycle time, while four-way coupled CFD–DEM has been used to resolve multiphase flow, particle trajectories, and particle–particle interactions (Fatahi & Farzanegan, 2017, 2018). Water-flow simulations and more recent flow-field analyses reinforce the conclusion that rotational intensity and fluidization conditions act through local velocity and pressure fields rather than through G alone (Fatahi & Farzanegan, 2019; Li, Zhou, Su, et al., 2024; Yuan et al., 2024). Experimental optimization and interpretable machine learning reach the same engineering conclusion from a different direction: feed density, operating settings, and feed properties can materially alter grade and recovery even when equipment geometry is fixed (Frigger et al., 2024; Li, Zhou, Liu, et al., 2024; Saim et al., 2025).

3.2 Falcon SB, C, and UF concentrators

Falcon concentrators comprise distinct architectures rather than simple size variants of one machine. SB units combine a smooth stratification zone with fluidized retention zones and are commonly operated semi-batch; C-type units emphasize flowing-film separation with continuous concentrate discharge; and UF bowls use high centrifugal intensity, a thin flowing layer, and a smooth retention zone for ultrafine duty. These designs impose different hydrodynamic and

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capacity boundary conditions and therefore different scale-up priorities. Reviews and experimental studies show strong sensitivity to feed particle size, density contrast, fluid velocity, bowl geometry, residence time, solids loading, and the interaction between centrifugal and hydrodynamic forces (Farajzadeh & Chehreh Chelgani, 2022; Singh, Kishore, et al., 2020; Singh, Sahu, Chalavadi, Swain, et al., 2021).

Ultrafine operation is particularly instructive. Dehaine et al. (2019) identified time-dependent separation phases and particle resuspension in Falcon UF operation, which is inconsistent with a simple stationary-settling interpretation. Laboratory Falcon work on mineral fines and later scheelite studies further shows that feed size, density, liberation, solids concentration, and bowl configuration strongly condition selectivity (Das, Kundu, et al., 2023; Das, Tan, et al., 2023; Marion et al., 2017). In historical scheelite tailings, feed-tank design and particle-size distribution (PSD) influenced performance strongly, whereas changes in G within the tested range had comparatively limited effect (Bru et al., 2026). Applications to coal, rare earths, phosphates, bentonite, copper, tantalum–niobium, and tin–niobium–tantalum by-products confirm a broad operating domain, but they also demonstrate that favorable Falcon settings are inseparable from mineralogy and feed preparation (Çerik, 2026; Demeusy et al., 2026; Hassan et al., 2025; Ibrahim et al., 2026; Norgren & Anderson, 2021a, 2021b; Schriner & Anderson, 2015; Zhang et al., 2019, 2022).

3.3 Multi-Gravity Separators

The MGS combines rotation, an inclined cylindrical surface, wash water, oscillatory motion, and dense-layer transport along the drum. The high-density product is therefore governed by more than centrifugal acceleration: axial transport, hydraulic washing, film or stratified-layer thickness, particle–particle interactions, and residence time are all adjustable. Statistical studies on iron ore and coal show strong interactions among operating variables (Chaurasia & Nikkam, 2017a, 2017b, 2017c; Chaurasia et al., 2018; Rao et al., 2017). More recent work makes the scale-up implication

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explicit. Çerik and Şen (2026) found that increasing drum speed favored recovery but reduced Fe grade within the tested range, whereas increasing wash water and slope improved grade while reducing recovery. These opposing responses demonstrate that rotational intensity cannot be scaled independently of hydraulic washing and residence behavior.

MGS applications to coking coal, nickel–cobalt laterites, pyrite-rich polymetallic material, and boron minerals further emphasize the effects of mineralogy, particle size, particle shape, and feed loading on the operating window (Andavarapu et al., 2023; Eljoudiani et al., 2025, 2026; Tok et al., 2025). MGS therefore provides a clear illustration of the "beyond nominal G" argument: scale-up must preserve or re-establish the combined transport field created by rotation, inclination, oscillation, wash water, stratified-layer behavior, and residence time rather than any single rotational parameter.

3.4 Other enhanced-gravity architectures and comparative boundaries

Enhanced-gravity concepts also appear in centrifugal classifiers, fluidized centrifugal separators, compound-force fields, recycling applications, and hybrid flowsheets. Studies of centrifugal fluidized separators and compound force fields show that density ratio, Stokes number, and fluid flow can determine trajectory and separation boundaries (Ma et al., 2019; Phirommark et al., 2023; Singh, Sahu, Chalavadi, Singh, et al., 2021). Applications to printed-circuit boards and lithium-ion-battery materials illustrate how liberation and density contrast can be engineered by pretreatment before centrifugal separation (Xian et al., 2021; Zhan & Pan, 2022). Gold recovery combining centrifugal gravity and flotation further illustrates the influence of circuit configuration (Valderrama et al., 2026). Comparative studies likewise show that equipment selection is inseparable from feed size, liberation, and product specification (Aras & Taner, 2023; Arthur et al., 2025; Metwally et al., 2025).

Figure 1 provides the conceptual map used throughout the review. It separates operating scale from equipment architecture and frames laboratory-to-pilot-to-industrial transfer as a multi-

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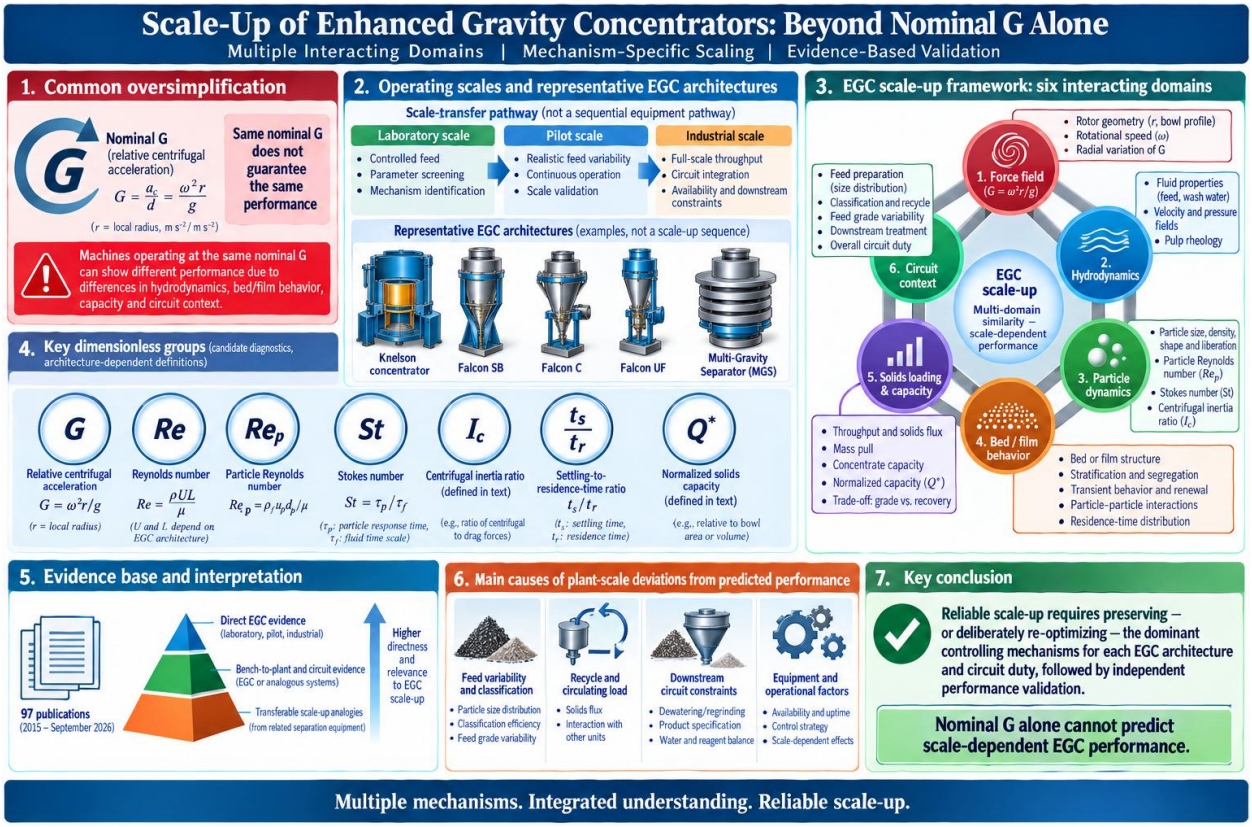
domain similarity problem in which force field, hydrodynamics, particle dynamics, bed/film behavior, solids loading and capacity, and circuit context must each be checked rather than assumed to follow nominal G.

Figure 1. *Scale-up of enhanced gravity concentrators: why nominal G alone does not preserve dynamic similarity*



Note. Original synthesis developed for this review; mechanistic concepts are based on Chen, Yang, Tong, Niu, et al. (2020), Çerik and Şen (2026), Dehaine et al. (2019), Farajzadeh and Chehreh Chelgani (2022), and Fatahi and Farzanegan (2018).

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4. Beyond Nominal G: Fundamentals Governing Separation

4.1 Centrifugal acceleration and spatial G distribution

For a particle located at radius r in a bowl rotating at angular velocity ω, the local centrifugal acceleration is $a_c = \omega^2 r$. The corresponding acceleration ratio relative to gravity is

$$G = \omega^2 r / g \quad (1)$$

Equation (1) illustrates why a single machine-level value of G is incomplete: centrifugal acceleration varies with radial position, and the dynamically relevant radius can differ among the feed-entry, stratification, film, and retention zones. If a larger radius is used while G is held constant, then $\omega \propto r^{-1/2}$, whereas peripheral velocity $u_\theta = \omega r$ scales as $r^{1/2}$. Wall shear, free-surface or film transport, and collision velocities can therefore change even when G is nominally preserved. This spatial interpretation is consistent with Knelson operating-mechanism, flow-field, and trajectory studies (Chen, Yang, Tong, Liu, et al., 2020; Fatahi & Farzanegan, 2019; Yuan et al., 2024).

4.2 Differential settling under enhanced gravity

In the Stokes limit, a first-order estimate of radial slip velocity for an isolated spherical particle in a Newtonian fluid under centrifugal acceleration is

$$v_r \approx (\Delta\rho\, d_p^2\, \omega^2\, r) / (18\, \mu) \quad (2)$$

where $\Delta\rho$ is the particle–fluid density difference, d_p is particle diameter, and μ is dynamic viscosity. Equation (2) is a limiting relation rather than a complete EGC model: it assumes low particle Reynolds number, dilute conditions, and negligible hindered settling, turbulence, particle shape effects, and interparticle interactions. Even within that simplified limit, G acts together with d_p^2, $\Delta\rho$, and μ. Identical G values therefore cannot compensate for changes in rheology, PSD, or liberation. Size-by-size responses observed in Knelson and Falcon studies are consistent with this sensitivity (Das, Kundu, et al., 2023; Marion et al., 2019; Zhang, Yang, Hou, et al., 2023; Zhang,

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Yang, Zhao, et al., 2023; Zhou et al., 2016). Outside the Stokes regime, the migration velocity v_r used in later similarity analysis should be obtained from the most defensible architecture- and regime-specific correlation, direct measurement, or independently validated CFD/DEM result; Equation (2) should not be used automatically for industrial feeds.

4.3 Particle size, density, shape, and liberation

Particle properties affect both the driving force for migration and the resistance to motion. Density contrast is central, but particle shape, composite mineralogy, and degree of liberation modify drag, effective density, contact mechanics, and whether a valuable phase can behave as an independently separable particle. Mineralogical studies of Nechalacho and other rare-metal systems show that density alone is insufficient because valuable-mineral associations and size-dependent liberation determine which particles are physically available for gravity separation (Filippov et al., 2016; Foucaud et al., 2019; Jordens, Marion, Langlois, Grammatikopoulos, Rowson, et al., 2016; Jordens, Marion, Langlois, Grammatikopoulos, Sheridan, et al., 2016; Marion et al., 2018). Automated mineralogy provides a direct bridge between liberation distributions and metallurgical response, which becomes especially important when scale-up changes PSD through different classification or recycle behavior (Pereira, 2026).

4.4 Fluid drag, turbulence, and slurry rheology

The fluid phase controls drag, entrainment, resuspension, fluidization where applicable, wash-water transport, and the thickness or holdup of the active separation layer. An architecture-specific equipment-scale Reynolds number can be written as

$$Re = \rho_f U L / \mu \quad (3)$$

where ρ_f is fluid density, U is a characteristic fluid velocity, L is a characteristic length, and μ is dynamic viscosity. The choices of U and L must be stated for each architecture because a bowl film, fluidized retention zone, and oscillating drum do not share one universal characteristic scale.

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A particle Reynolds number, Re_p, defined from particle slip velocity and d_p, is more appropriate for particle-scale drag. If L, U, solids concentration, or apparent viscosity changes with scale, the hydrodynamic regime can change despite equal G. Falcon velocity measurements and fluid-dynamic studies connect separation directly to local flow behavior (Dehaine et al., 2019; Singh, Kishore, et al., 2020). Knelson CFD and CFD–DEM studies show analogous sensitivity to geometry and operating conditions (Fatahi & Farzanegan, 2018, 2019; Ma, Wei, Zhu, Xu, et al., 2021). Clay-containing feeds provide an additional warning: fines can alter rheology and the water–particle environment sufficiently to degrade separation (Basnayaka et al., 2020). Provisional architecture-specific choices of U and L are summarized in Table 4; they are reporting conventions for testing similarity, not universal definitions.

4.5 Stratification, bed/film rearrangement, and retention

The final concentrate is often produced through repeated rearrangement within a finite retained bed, retention zone, or flowing/retained film rather than by a single settling event. Knelson retained-mass models and ring-by-ring analyses show that loading evolves spatially and can become capacity-limited (Chen, Yang, Tong, Lin, et al., 2020; Chen et al., 2026; Ghaffari & Farzanegan, 2017a, 2017b, 2018). Falcon UF kinetics show that initially captured material can be resuspended, making treatment time and transient film history part of the separation mechanism (Dehaine et al., 2019). Scale effects are also well established in granular rotating systems, where matching one kinematic quantity does not preserve segregation or mixing when the equipment-to-particle size ratio changes (He et al., 2024; Herman et al., 2022; Xu et al., 2024). These analogies support, but do not independently prove, the need to test bed/film-state similarity in EGC scale-up.

Figure 2 compares the dominant mechanisms of the principal EGC architectures. The figure is intended as an architecture-specific scale-up guide: Knelson, Falcon SB, Falcon C, Falcon UF,

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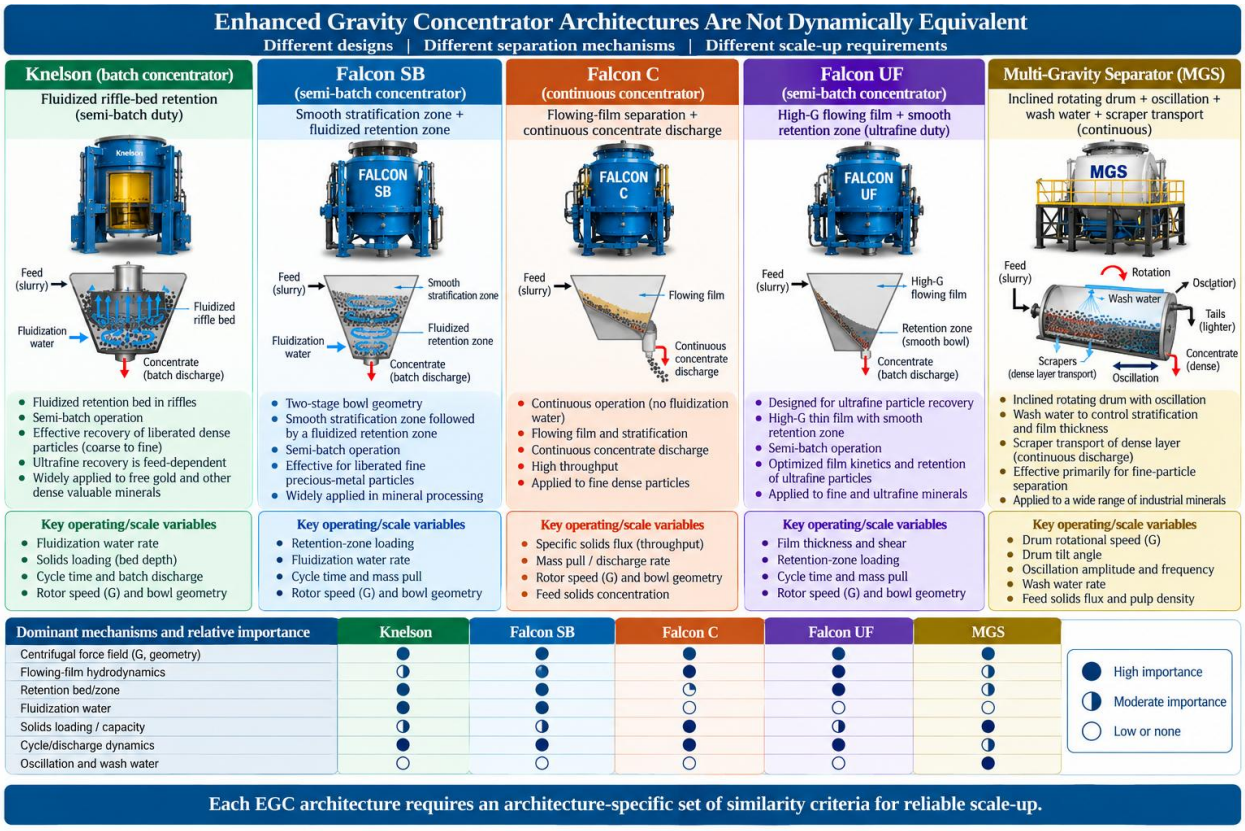
and MGS emphasize different combinations of retained-bed behavior, flowing-film transport, fluidization or wash water, solids loading, discharge dynamics, and transient particle behavior.

Figure 2. *Mechanistic comparison of major EGC architectures and architecture-specific scale-up variables*



Note. Original synthesis. Mechanistic descriptions are based on Chen, Yang, Tong, Niu, et al. (2020), Çerik and Şen (2026), Dehaine et al. (2019), Farajzadeh and Chehreh Chelgani (2022), and Singh, Kishore, et al. (2020).

5. Why Laboratory Similarity Does Not Guarantee Industrial Similarity

Table 2 organizes the six principal similarity domains that can change between scales even when nominal G is preserved and pairs each with practical diagnostic measurements. The purpose

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is to identify the changed domain before attempting to compensate empirically by adjusting speed, water, or throughput.

Table 2. *Scale-dependent variables that can break dynamic and metallurgical similarity*

Domain	Variable or ratio	Why it changes with scale	Recommended diagnostic
Force field	Radius, angular speed, bowl/drum geometry, characteristic length, G(r)	Changes local acceleration, peripheral velocity, active area, and separation-layer volume	Dimensioned geometry map; local G(r); peripheral velocity
Hydrodynamics	Architecture-specific Re, superficial velocity, film/bed thickness, velocity/pressure field, rheology, RTD	Flow, water delivery, holdup, and characteristic scales rarely change proportionally	Velocity/pressure measurements or validated CFD; rheology; film/bed thickness; tracer RTD
Particle dynamics	d_p/L, Δρ, Re_p, St, liberation, density and shape distributions	Feed preparation, classification, and recycle change PSD, density contrast, and particle associations	Size-by-size mineralogy; liberation; density/shape classes; size-by-size partition
Bed/film behavior	Retained mass or solids holdup, porosity, film/bed structure, stratification, resuspension, cycle time	Retention, film renewal, and saturation can change nonproportionally with scale and loading	Retained mass/holdup versus time and position; bed expansion or film-state measurements
Solids loading & capacity	Specific solids flux, mass pull, normalized capacity, cycle/discharge load	Industrial loading can outpace active area, retention volume, or discharge capacity	Specific solids flux; mass pull; retained mass; discharge/capacity test
Circuit context	Feed preparation/classification, recycle, feed grade/PSD variability, duty, availability, downstream recovery	Industrial EGCs operate inside dynamic circuits and under equipment and downstream constraints	Plant mass balance; uptime; recycle PSD; classifier partition; downstream extraction/recovery

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Note. The diagnostic approach synthesizes the EGC mechanisms reviewed in Sections 4–9 with transferable residence-time and scale-up concepts (He et al., 2024; Herman et al., 2022; Rodrigues, 2021).

5.1 Geometry and characteristic length

Geometric enlargement changes more than nominal capacity. Radius changes the spatial acceleration field; bowl depth changes available migration distance and residence; ring dimensions alter retention volume; and feed-entry geometry changes momentum and initial trajectory. Laboratory Knelson studies show substantial size- and configuration-dependent responses even in standardized small bowls (Kökkılıç et al., 2015; Marion et al., 2019; Zhou et al., 2016). A commercial machine therefore cannot be assumed dynamically similar simply because it belongs to the same equipment family.

5.2 Throughput and solids flux

Industrial throughput may increase nonproportionally to active separation area, retained-bed volume, film area, or discharge capacity. A more informative variable is specific solids flux, J_s = ṁ_s/A_eff, or another architecture-specific loading measure normalized by active area, retention capacity, or discharge capacity. Continuous centrifugal-concentrator studies show that mass yield, feed density, and operating variables must be tuned jointly rather than scaled independently (Altun et al., 2015; Pelikh et al., 2020, 2021; Sakuhuni et al., 2015, 2022). Falcon and MGS applications similarly show that increasing solids concentration can change drag, crowding, film or layer structure, and product yield (Özgen, 2017; Zhang et al., 2024).

5.3 Residence-time distribution

Scale-up discussions often use a single nominal residence time, although nonideal flow produces a residence-time distribution (RTD). Short-circuiting can reduce exposure to the active separation region, whereas long tails can increase recirculation, crowding, or resuspension. RTD theory therefore provides a useful bridge between hydrodynamics and metallurgical response (Rodrigues, 2021). For EGCs, the relevant quantity is the distribution of time spent in the active

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migration, retention, or washing region, not simply equipment volume divided by volumetric flow rate.

5.4 Film thickness and slurry holdup

Falcon C and UF operation is especially sensitive to film thickness and slurry holdup because migration must occur within a moving layer. A thicker film increases characteristic migration distance and can alter shear, residence, and particle collision frequency. Fluid-velocity and UF-kinetics studies show that local flow and transient retention influence partitioning (Dehaine et al., 2019; Singh, Kishore, et al., 2020). Related enhanced-gravity classification and fine-coal studies also show that particle migration depends on the interaction between size, flow, and treatment time (Zhang, Yang, Hou, et al., 2023; Zhu et al., 2017).

5.5 Fluidization- and wash-water scaling

For fluidized-retention architectures, especially Knelson and Falcon SB, water delivery is part of the separation mechanism rather than an auxiliary setting. Scaling only total volumetric water flow can change superficial velocity, pressure drop, local bed expansion, and the balance between selective rearrangement and elutriation. Knelson water-flow and multiphase simulations show that rotational intensity and fluidization jointly determine local pressure and velocity fields (Chen, Yang, Tong, Liu, et al., 2020; Fatahi & Farzanegan, 2018, 2019). MGS wash water serves a different hydraulic-washing function and should be scaled against drum geometry, solids loading, and residence behavior rather than treated as equivalent to bed fluidization. A scale-up protocol should therefore report water flow per active area, pressure or hydraulic head where relevant, and an observed or modeled bed/film-state indicator.

5.6 Concentrate capacity and mass pull

Retention devices have finite concentrate or retention capacity, whereas continuous devices have finite mass-pull and discharge capacity. If feed loading increases more rapidly than effective

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capacity, the machine can saturate or overload, alter the grade–recovery relationship, or require a different cycle, throughput, or discharge setting. Knelson retained-mass models explicitly demonstrate this constraint (Chen, Yang, Tong, Lin, et al., 2020; Ghaffari & Farzanegan, 2017a), while continuous CVD modeling emphasizes joint control of grade, recovery, and mass yield (Sakuhuni et al., 2022). Capacity similarity must therefore be checked explicitly and on a consistent loading basis rather than inferred from equal G.

6. Candidate Dimensionless and Mechanistic Diagnostics for Scale-Up

A useful scale-up framework should reduce a large set of dimensional variables to ratios that represent dominant physical balances. Table 3 lists candidate quantities for this purpose. They are not presented as a universal Buckingham-Π solution or as validated scale-up laws. Rather, they provide a disciplined diagnostic vocabulary for asking which force, flow, particle-response, particle-to-active-zone scale, residence, oscillatory, and capacity balances should remain comparable for a particular architecture and circuit duty. Because the graphical abstract and Figure 1 use simplified symbols, the formal notation adopted below is cross-referenced explicitly in Table 3. The underlying logic follows classical dimensional-similarity reasoning: dimensionless groups are useful only when they preserve the balances relevant to the mechanism of interest (Buckingham, 1914), while particulate systems additionally require explicit attention to collective settling or fluidization effects when concentrations depart from the dilute limit (Richardson & Zaki, 1954).

Table 3. *Candidate mechanistic and dimensionless quantities for EGC scale-up*

Quantity	Expression	Physical meaning	Primary relevance
Centrifugal acceleration ratio, G	$\omega^2 r/g$	Local centrifugal acceleration relative to gravity	All rotating EGCs; foundational descriptor, insufficient alone
Reynolds number, Re	ρ_fUL/μ	Architecture-specific inertial-to-viscous flow balance	Film, wash/fluidization-water, and feed hydrodynamics

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Quantity	Expression	Physical meaning	Primary relevance
Particle Reynolds number, Re_p	ρ_f|u_p−u_f|d_p/μ	Particle-scale drag regime	Fine and ultrafine particle migration
Stokes number, St	τ_pU/L	Particle response time relative to characteristic flow time	Trajectory following, entrainment, and inertial lag
Centrifugal flow-inertia ratio, I_c	$U^2/(a_cL)$	Flow inertia relative to centrifugal forcing	Free-surface, flowing-film, and rotating-layer similarity; diagnostic only
Migration-to-residence ratio, Π_s	v_rτ/L_r = t_r/t_s	Migration opportunity relative to required cross-layer travel	Falcon C/UF and other film/classification duties
Normalized solids-capacity loads, Λ_b and Λ_c	Λ_b = m_s,cycle/M_cap; Λ_c = ṁ_s/ṁ_cap	Semi-batch retention loading and continuous discharge loading	Overload/saturation diagnostics; capacities must be measured or independently modeled
Particle-to-active-zone scale ratio, d_p/L_a	d_p/L_a	Particle size relative to the architecture-specific active-zone length	Geometric enlargement when particle size does not scale; all EGCs
MGS oscillatory exposure descriptors	A/L_a; fτ; 2πf/ω	Oscillation amplitude relative to layer scale, cycles experienced during residence, and oscillation-to-drum frequency ratio	MGS only; provisional architecture-specific diagnostics

Note. The groups combine EGC-specific mechanisms with transferable fluid- and particle-similarity concepts. Re and related similarity arguments are widely used in other centrifugal separators, including cyclones (Misiulia et al., 2024; Pandey et al., 2022), but no numerical cyclone correlation is assumed to

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apply directly to EGCs. I_c is used preferentially here to avoid implying an established universal centrifugal Froude law. The graphical abstract and Figure 1 use simplified aliases: t_s/t_r = 1/Π_s when t_s = L_r/v_r and t_r = τ, and Q denotes normalized capacity. Characteristic U, L, L_a, τ_p, τ, and migration distance L_r must be defined for the architecture and active zone under study. The MGS oscillatory descriptors are architecture-specific and provisional.*

6.1 Centrifugal acceleration ratio

G is a foundational descriptor because it defines imposed centrifugal acceleration relative to gravity, but preserving one nominal G value is not, by itself, a sufficient scale-up condition. Equation (1) should therefore be applied as a spatial field rather than as a single nameplate value. Where bowl or drum radii span a meaningful range, G(r) should be reported at feed-entry, active separation, retention, and discharge regions as appropriate. This practice makes cross-machine comparison more transparent and is consistent with flow-field and trajectory studies (Li, Zhou, Su, et al., 2024; Yuan et al., 2024).

6.2 Reynolds and particle Reynolds numbers

Re and Re_p differentiate equipment-scale flow from particle-scale drag behavior. Maintaining one definition of Re during scale-up may require flow-rate changes that conflict with throughput or capacity goals, and the characteristic U and L are architecture-specific. Exact similarity can therefore be impossible. Scale-up should focus on the dimensionless groups linked to the dominant mechanism and state explicitly which groups are not preserved. Cyclone research illustrates the diagnostic value of Reynolds-number similarity, while Falcon studies show EGC separation sensitivity to local velocity and flow structure (Misiulia et al., 2024; Singh, Kishore, et al., 2020). For fluidized-retention devices, pressure drop and bed expansion should be checked alongside superficial water velocity because equivalent volumetric water rate alone does not establish equivalent fluidization.

Table 4. Provisional architecture-specific characteristic scales for Reynolds-type analysis

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Architecture/active zone	Candidate characteristic velocity, U	Candidate characteristic length, L	Additional state variable to report
Knelson fluidized retention zone	Superficial fluidization-water velocity or local interstitial velocity	Characteristic riffle spacing, bed depth, or hydraulic diameter of the active retention zone	Pressure drop, bed expansion/porosity, retained mass
Falcon SB retention zone	Superficial fluidization-water velocity and/or local slurry velocity entering retention zone	Retention-zone depth or characteristic groove/active-zone dimension	Pressure drop, bed expansion, cycle loading
Falcon C flowing film	Mean active-film velocity	Film thickness for local Re; active radial length for residence-scale analysis	Film thickness, shear, mass pull/discharge rate
Falcon UF flowing/retention layer	Mean thin-film velocity or local slurry velocity	Film thickness or retention-layer thickness; active radial length where appropriate	Resuspension, transient holdup, cycle history
MGS stratified oscillating layer	Mean relative layer velocity or axial layer-transport velocity	Characteristic layer thickness or active drum length, stated explicitly	A, f, tilt, wash-water flux, fτ, and 2πf/ω

Note. These definitions are candidate reporting conventions, not universal similarity laws. U and L should be chosen to represent the dominant transport mechanism and must be declared explicitly. For fluidized

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Knelson/Falcon SB zones, pressure drop and bed expansion supplement velocity similarity; for MGS, oscillatory descriptors supplement Reynolds-type quantities.

6.3 Stokes number and particle relaxation

The Stokes number compares particle response time, τ_p, with a characteristic flow time, L/U. In the Stokes regime, τ_p is commonly proportional to $\rho_p d_p^2/\mu$; thus, St changes with particle size, density, fluid viscosity, and the selected velocity and length scales. Low-St particles follow rapid fluid variations more closely and are more susceptible to entrainment or resuspension, whereas higher-St particles exhibit greater inertial lag. Classification work in centrifugal fields shows that Stokes number and density ratio can explain microscopic particle behavior (Phirommark et al., 2023). Matching G while allowing St to change can therefore move target particles into a different trajectory regime.

6.4 Centrifugal flow-inertia similarity

A centrifugal flow-inertia ratio is denoted $I_c = U^2/(a_c L)$, comparing characteristic flow inertia with centrifugal forcing over length L. The symbol I_c is used preferentially to avoid implying that an established universal centrifugal Froude law exists for EGCs. I_c is a diagnostic ratio only and is most relevant where free-surface, flowing-film, or rotating-layer behavior controls transport. Rotating-drum studies show that Froude-type similarity can be necessary yet insufficient when equipment-to-particle size ratio is not preserved (He et al., 2024; Herman et al., 2022). The implication for EGCs is that global kinematic similarity does not guarantee particle-scale similarity; d_p/L_a should therefore be examined independently.

6.5 Migration-to-residence-time ratio

For a particle to report to a dense-product region, it must migrate a characteristic cross-film or radial distance before leaving the active zone. A useful diagnostic ratio is

$$\Pi_s = v_r \tau / L_r \quad (4)$$

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where v_r is the most defensible architecture- and regime-specific slip or migration velocity, τ is the residence time within the active separation zone, and L_r is the characteristic migration distance across that zone. Equation (2) provides v_r only in its stated Stokes-limit domain; outside that domain, v_r should come from a validated drag relation, measurement, or independently validated CFD/DEM result. L_r must also be architecture-specific—for example, an effective film thickness in Falcon C/UF or an effective cross-layer/retention distance in other designs—and τ should represent active-zone residence rather than total equipment volume divided by bulk flow. With $t_s = L_r/v_r$ and $t_r = \tau$, $\Pi_s = t_r/t_s$; the graphical abstract and Figure 1 display the inverse form, t_s/t_r. Neither form is a sufficient recovery criterion because turbulence, crowding, bed/film interactions, and resuspension can reverse or delay migration. The ratio remains a physically interpretable diagnostic of competition between migration kinetics and available treatment time (Dehaine et al., 2019; Sakuhuni et al., 2016).

6.6 Solids-loading and normalized-capacity criteria

Capacity similarity requires loads defined on a consistent time basis. For semi-batch retention devices, $\Lambda_b = m_{s,cycle}/M_{cap}$ expresses cycle solids loading relative to an empirically measured or independently modeled retention capacity. For continuous devices, $\Lambda_c = \dot{m}_s/\dot{m}_{cap}$ expresses solids rate relative to an effective discharge or mass-pull capacity. These ratios are valuable overload and saturation diagnostics, but they are not fully a priori predictive because M_{cap} and $\dot{m}_{cap}$ generally require independent measurement or validated modeling. The graphical abstract and Figure 1 use the simplified capacity symbol Q*. The purpose is not to prescribe a universal coefficient but to make crowding, saturation, and discharge limitation explicit. Retained-mass modeling, plant-scale CVD optimization, and circuit studies support capacity-normalized interpretation (Altun et al., 2015; Ghaffari & Farzanegan, 2017a; Sakuhuni et al., 2022).

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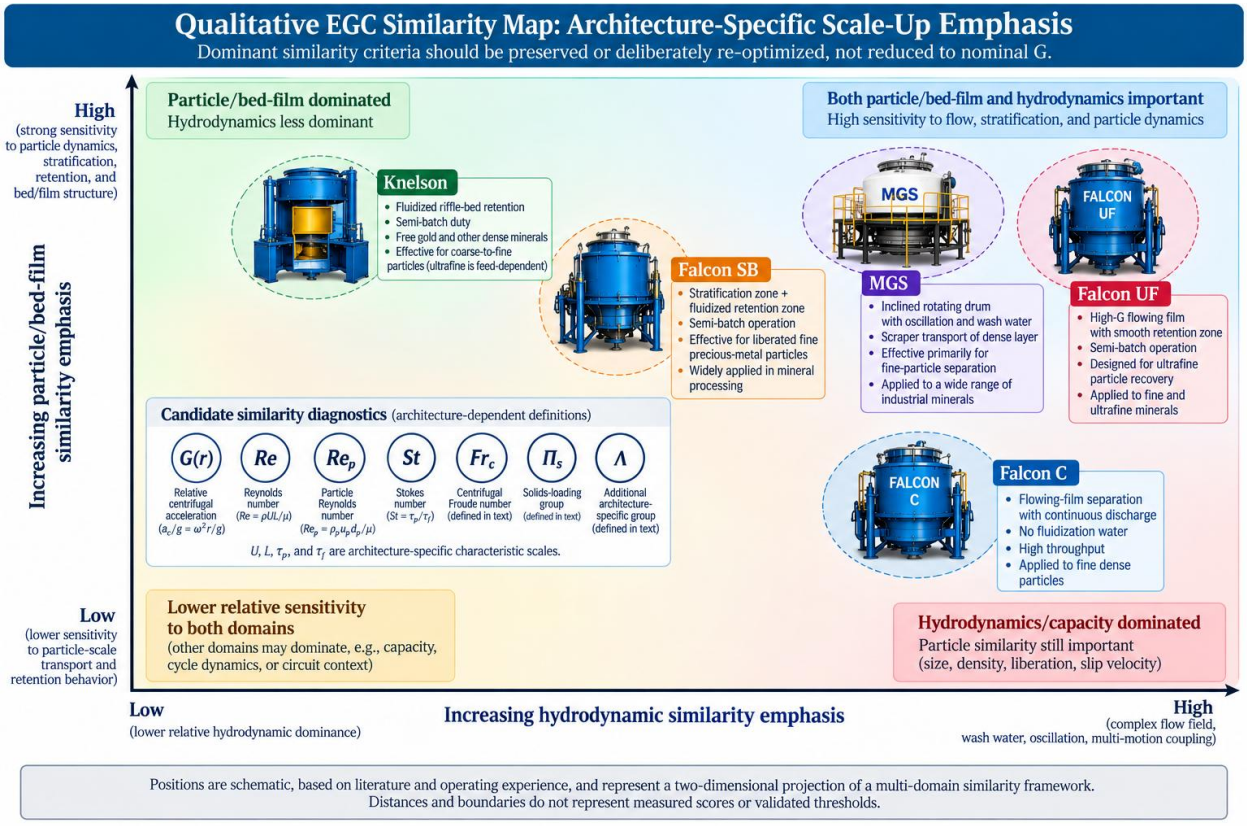
Figure 3 provides a qualitative two-dimensional projection of the multi-domain framework. It contrasts relative hydrodynamic scale-up emphasis with particle/bed-film emphasis for the principal architectures. The positions are literature-informed and schematic; distances, quadrants, and marker locations are not measured scores, rankings, or validated numerical thresholds.

Figure 3. *Qualitative EGC similarity map: architecture-specific scale-up emphasis*



Note. Original synthesis. Candidate groups are based on Equations (1)–(4), particle-dynamics concepts, EGC flow studies, and transferable scale-up principles from He et al. (2024), Herman et al. (2022), Misiulia et al. (2024), Phirommark et al. (2023), and Rodrigues (2021). Marker positions are schematic and represent a two-dimensional projection of a multi-domain problem, not quantitative rankings or validated thresholds.

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7. Equipment-Specific Scale-Up

7.1 Knelson: fluidized retention beds

Knelson scale-up should be evaluated through a coupled set of local G distribution, superficial fluidization-water velocity or pressure, specific solids flux to active retention regions, cycle or discharge behavior, and normalized retained mass. Laboratory optimization is useful for identifying sensitivities but is not, by itself, evidence of cross-scale transfer. Feed density can dominate laboratory grade and recovery, and ring filling evolves with both time and position (Chen, Yang, Tong, Lin, et al., 2020; Frigger et al., 2024). Studies across dry and fine-mineral laboratory duties further show persistent particle-size and feed-property effects (Kökkılıç et al., 2015; Marion et al., 2019; Zhou et al., 2016). Equivalent fluidization cannot be established from volumetric water rate alone; superficial velocity, pressure drop, distributor geometry, bed expansion/porosity, and particle mixture should be checked together.

7.2 Falcon SB: retention-zone scaling

For Falcon SB, scale-up should preserve or re-establish retention-zone loading, fluidization-water conditions, cycle time, specific feed flux, and the hydrodynamic conditions delivering particles from the smooth stratification zone to the retention zones. Semi-batch experiments show that capture can become constrained by the balance between centrifugal migration and displacement or entrainment in the flowing slurry (Singh, Sahu, Chalavadi, Swain, et al., 2021). Studies on chromite, scheelite, and other feeds show that favorable settings shift with PSD and mineralogy, reinforcing the need for size-by-size validation rather than transfer of a single operating point (Das, Tan, et al., 2023; Freire et al., 2019). Equivalent fluidization cannot be established from volumetric water rate alone; superficial velocity, pressure drop, distributor geometry, bed expansion/porosity, and particle mixture should be checked together.

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7.3 Falcon C: continuous flowing-film and mass-pull scaling

Falcon C scale-up requires a flowing-film, loading, and continuous-discharge perspective. Direct multi-size scale-up evidence for Falcon C remains limited in the curated corpus. Gravity Release Analysis and CVD optimization studies on other continuous centrifugal concentrators nevertheless provide a transferable process-design analogy: laboratory release behavior can estimate amenability and mass-yield range, while the continuous unit must then be tuned under grade, recovery, loading, and discharge-capacity constraints (Sakuhuni et al., 2016, 2022). These studies support a capacity-based transfer philosophy but should not be treated as direct proof of Falcon C geometric similarity.

7.4 Falcon UF: thin-film ultrafine separation

Falcon UF scale-up should prioritize flowing-film hydrodynamics, particle-scale drag, feed PSD, retention-zone loading, and transient capture–resuspension behavior. The kinetics reported by Dehaine et al. (2019) and the performance differences between fluidized and UF bowls reported by Das, Tan, et al. (2023) show that a static partition model can miss time-dependent effects. In highly weathered ultrafine tailings, upstream desliming and feed delivery can influence selectivity more strongly than moderate changes in G (Bru et al., 2026). Scale-up test work should therefore control feed-tank, pumping, conditioning, and solids-loading configurations instead of treating bowl speed as the sole transferable setting.

7.5 MGS: drum speed, tilt, wash water, and oscillation

MGS scale-up is intrinsically multivariable. Drum speed changes the centrifugal field and particle holdup; slope changes axial transport and residence time; wash water changes hydraulic drag and gangue displacement; and oscillation changes stratified-layer renewal and axial transport. Experimental-design studies on coal and iron ore consistently identify interaction effects and nonlinear response surfaces (Chaurasia & Nikkam, 2017a, 2017b, 2017c; Rao et al., 2017). In

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specularite beneficiation, settings that improved grade could reduce recovery, and vice versa (Çerik & Şen, 2026). An MGS scale-up protocol should therefore target the combined rotation–inclination–oscillation–wash-water transport field, together with solids loading and RTD, rather than rotational speed alone.

8. From Bench to Pilot to Plant: What the Published Evidence Actually Shows

Direct bench-to-plant evidence remains less abundant than fixed-scale optimization studies. Table 5 summarizes representative evidence and distinguishes direct industrial translation from predictive, circuit-scale, or mechanism-transfer evidence. Across these cases, transfer quality depends on whether test work captures the industrial duty, including recycle load, feed variability, equipment availability, classification, and downstream concentrate handling.

Table 5. Representative evidence relevant to bench-to-pilot/plant translation

Study or evidence type	Scale link	Main scale-up lesson
Sakuhuni et al. (2016). Gravity Release Analysis	Batch laboratory → continuous centrifugal concentration	Use laboratory release behavior to estimate amenability and mass-yield range; do not transfer settings directly.
Altun et al. (2015), grinding-circuit continuous concentration	Circuit-scale continuous application	Circuit recycle and grinding duty determine feed PSD, feed grade, and required mass pull.
Rajala (2021), Otjikoto gold mill	3-in. laboratory Knelson testing → four QS48 plant units	Plant recovery differed from the design expectation because availability, feed variability, classification, and downstream intensive-leach performance intervened.
Sakuhuni et al. (2022), CVD hybrid optimization	Plant data and model tuning	Multiobjective optimization can tune continuous operation, but validity remains domain-specific.

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Study or evidence type	Scale link	Main scale-up lesson
Bru et al. (2026), ultrafine scheelite	Laboratory flowsheet development (predictive evidence)	Feed PSD and feed-system configuration can dominate G within the tested range; scale-up must include upstream delivery effects.
Çerik and Şen (2026), MGS optimization	Laboratory parameter map (mechanistic/optimization evidence)	Opposing grade and recovery responses show that single-variable similarity is inadequate.

Note. The table distinguishes predictive transfer, circuit evidence, and direct geometric scale-up. Plant discrepancies indicate that circuit context, equipment availability, classification, and downstream recovery must be included in scale-up closure; they do not imply that enhanced gravity concentration is intrinsically unreliable.

The Otjikoto case is particularly informative because laboratory gravity-recovery testing and modeling were followed by operation of four industrial Knelson concentrators treating the full ball-mill circulating load. The published plant analysis reported realized gravity recovery below the design expectation and identified lower concentrator availability, lower-than-modeled intensive-leach extraction, possible variability in gravity-recoverable gold, and cyclone-classification differences as contributing factors (Rajala, 2021). The case highlights an important distinction: a test program can correctly identify gravity concentration as technically viable while still overpredicting plant recovery if equipment availability, downstream extraction, and circuit feed distributions are not adequately represented.

Other flowsheet studies reach the same conclusion across commodities. Integrated treatment of tungsten, rare-earth, and lithium-related ores shows that gravity performance depends on upstream liberation and on downstream combinations with flotation or magnetic separation (Foucaud et al., 2019; Jordens, Marion, Langlois, Grammatikopoulos, Rowson, et al., 2016; Jordens, Marion, Langlois, Grammatikopoulos, Sheridan, et al., 2016; Korbel et al., 2025). Centrifugal preconcentration can reduce grinding or flotation load, but that benefit changes the circuit conditions the separator experiences. The scaled unit should therefore be evaluated by circuit function and total recovery contribution, not isolated stage recovery alone (Altun et al., 2015; Klein et al., 2016).

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9. Modeling as a Scale-Up Tool: Empirical Models, CFD, DEM, CFD–DEM, and Data-Driven Approaches

Modeling can support scale-up only when the modeled physics and validation domain match the intended extrapolation. Empirical response surfaces, artificial neural networks, random forests, gradient boosting, and hybrid optimization can map operating windows effectively at a fixed machine size (Chaurasia & Nikkam, 2017a; Frigger et al., 2024; Ma, Wei, Zhu, Pei, et al., 2021; Saim et al., 2025; Zhang et al., 2024). Their scale-up limitation is structural: a model trained on speed, water, feed density, and related variables at one geometry contains no independent information about how characteristic length, active area, retention volume, or flow topology change with scale unless such variables or multiple geometries are represented explicitly in the training data.

Mechanistic models offer a stronger basis for transfer because DEM can resolve particle contacts and segregation, CFD can resolve velocity, pressure, and film fields, and coupled CFD–DEM can represent particle–fluid interactions. Knelson studies show that these methods can reproduce laboratory trends and reveal local quantities unavailable from bulk assays (Fatahi & Farzanegan, 2017, 2018, 2019; Ma et al., 2019; Yuan et al., 2024). Mechanistic sophistication, however, does not guarantee scale-up validity. Contact laws, turbulence closures, particle-shape assumptions, rheology, boundary conditions, mesh resolution, and computational coarse-graining can all become scale-dependent. Credible extrapolation therefore requires validation against an independent geometry, feed/mineralogical domain, or industrial data set.

A promising future strategy is hybrid: mineralogy and size-by-size measurements define particle populations; CFD/DEM or reduced-order models identify scale-sensitive variables; and data-driven methods calibrate uncertain closures and quantify nonlinear interactions. Multidimensional separation functions provide a useful language because they express recovery as a function of particle properties rather than as a single scalar cut size (Schach et al., 2025). This

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approach also explains why one machine can behave differently for rare-earth minerals, coal, chromite, and scheelite: each feed occupies a different region of particle-property space and may activate a different controlling mechanism.

10. Scale-Up Failure Modes and Diagnostic Indicators

The literature reveals recurring failure modes that can be diagnosed before or during industrial implementation. Table 6 links observable symptoms to likely broken similarity domains, diagnostic indicators, and corrective directions. The central principle is to identify the domain that changed with scale before compensating empirically by changing rotational speed, wash or fluidization water, or throughput. Applicability is architecture-dependent; in particular, fluidization diagnostics apply only to fluidized-retention designs.

Table 6. Scale-up failure modes, likely causes, and diagnostic indicators

Observed failure	Likely broken similarity	Diagnostic indicator	Corrective direction
Size-dependent recovery shifts at the same nominal G	Hydrodynamic or active-zone residence mismatch	G(r), architecture-specific Re, velocity/pressure field, film/bed thickness, specific feed flux, RTD	Correct flow/area, feed delivery, water delivery, or active-zone residence before changing G
Grade or recovery deteriorates as specific solids flux rises	Solids-loading or capacity mismatch	Specific solids flux, solids holdup, mass pull, retention/discharge capacity	Retune throughput, cycle/discharge, or effective capacity using architecture-specific loading limits
Compaction/channeling or fines elutriation in a fluidized-retention unit	Fluidization mismatch	Superficial water velocity, pressure drop, distributor/riffle area, bed expansion	Scale water with active geometry and bed state; applicable only to fluidized-retention architectures

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Observed failure	Likely broken similarity	Diagnostic indicator	Corrective direction
Grade–recovery or size-by-size response changes at nominally similar settings	Feed PSD, density-contrast, or liberation mismatch	Feed PSD, $\Delta\rho$ distribution, liberation/mineralogy, size-by-size partition	Restore representative feed preparation/classification or retune the operating window
Bench recovery is not reproduced in continuous plant operation	RTD or circuit-integration mismatch	Tracer RTD, circulating load, classifier partitioning, inventories, availability, downstream extraction	Retune circuit duty and close the plant mass balance, including availability and downstream recovery
High laboratory fit but poor pilot/plant prediction	Model-domain extrapolation	Extrapolation range, uncertainty, independent feed/geometry validation, CFD mesh and closure checks	Restrict model use to its validated domain or recalibrate with independent pilot/plant data
Mechanical/energy feasibility overlay	Hydrodynamically plausible similarity may be mechanically or energetically infeasible at larger scale	Installed power/torque, specific energy (kWh/t), total process-water demand, structural/bearing limits, and maintenance constraints	
Uncertainty and repeatability in direct scale comparisons	Apparent scale effects can be confounded by	Replicate tests, uncertainty/confidence intervals for grade	

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Observed failure	Likely broken similarity	Diagnostic indicator	Corrective direction
	analytical and run-to-run variability	and recovery where possible, and matched feed mineralogy across sizes	
Open pilot-to-plant datasets	Industrial validation is too sparse to separate machine effects from circuit effects consistently	Publicly documented geometry, feed, operating conditions, availability, mass balances, and downstream recovery for matched pilot/plant campaigns	

Note. Failure modes synthesize evidence from Knelson retained-mass and flow studies, Falcon kinetics and ultrafine applications, MGS multivariable optimization, continuous-circuit studies, and the Otjikoto plant case. Not every failure mode applies to every EGC architecture.

Figure 4 converts the failure-mode logic in Table 6 into a practical diagnostic sequence. The workflow begins with an observable symptom, then checks the relevant hydrodynamic, loading, feed, residence/circuit, or model-validity domain before any setpoint is changed. This ordering reflects industrial troubleshooting, where the broken similarity domain must be inferred from process measurements rather than assumed in advance.

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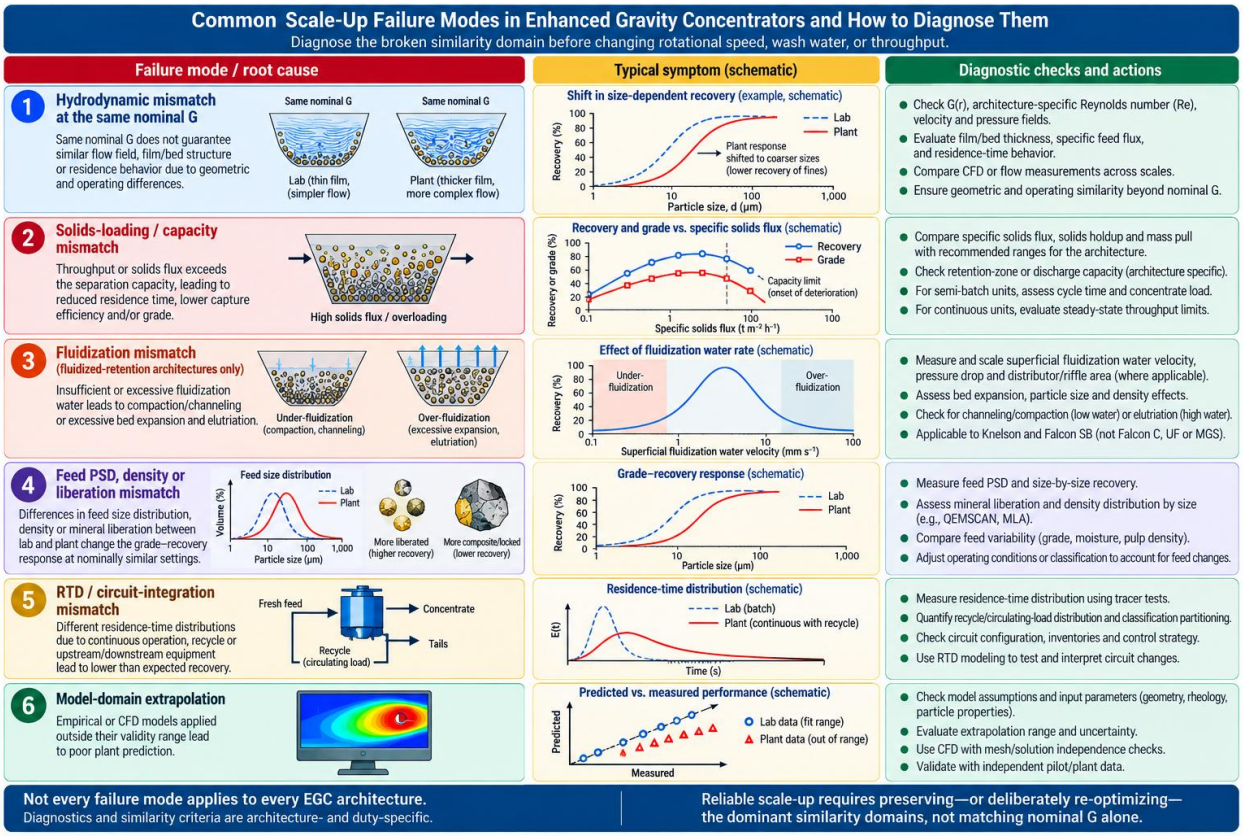
Figure 4. *Common scale-up failure modes in enhanced gravity concentrators and diagnostic actions*



Note. Original synthesis based on the failure patterns discussed in Sections 5–10, including Bru et al. (2026), Çerik and Şen (2026), Dehaine et al. (2019), Fatahi and Farzanegan (2018, 2019), Frigger et al. (2024), and Rajala (2021).

11. A Unified EGC Scale-Up Similarity Framework

The evidence supports an author-developed six-domain EGC Scale-Up Similarity Framework. The framework is conceptual and has not yet been prospectively validated as a predictive scale-up model. It is an umbrella structure for making assumptions explicit, not a complete universal similarity set. Exact geometric, hydrodynamic, particle, and capacity similarity is often impossible at industrial scale; architecture-specific descriptors therefore supplement the

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six common domains. The practical task is to identify the dominant mechanism and dominant similarity constraints, identify conflicts among those constraints, prioritize the quantities most strongly linked to metallurgical performance, deliberately re-optimize the remaining domains, and then validate independently. In this form, scale-up becomes an explicit, testable engineering argument rather than a single-number extrapolation.

The six domains are: (1) force-field similarity, defined by G(r), angular speed, local radius, geometry/profile, and spatial acceleration distribution; (2) hydrodynamic similarity, defined by architecture-specific Reynolds-type quantities, superficial velocities, film or bed thickness, velocity and pressure fields, turbulence, rheology, and water-delivery conditions; (3) particle-dynamic similarity, defined by particle size, particle–fluid density contrast, shape, mineralogy, liberation, Re_p, St, and migration velocity; (4) bed/film-behavior similarity, defined by retention or film structure, stratification, fluidization where applicable, resuspension, solids holdup, and transient accumulation/discharge behavior; (5) solids-loading and capacity similarity, defined by specific solids flux, solids holdup, mass pull, retention or discharge capacity, and grade–recovery–capacity trade-offs; and (6) circuit-context similarity, defined by feed preparation/classification, recycle or circulating load, feed variability, upstream liberation, downstream concentrate treatment, circuit duty, and equipment availability. Figure 5 presents these domains as interacting rather than independent checkboxes. Architecture-specific supplements include pressure-drop/bed-expansion descriptors for fluidized-retention zones, oscillatory descriptors for MGS, discharge behavior for continuous units, and transient resuspension/cycle-history descriptors for Falcon UF. A separate industrial-feasibility overlay should also be applied after similarity analysis, covering installed power and torque, specific energy consumption (kWh/t), total process-water demand, structural/bearing limits, maintenance burden, and other mechanical operating constraints.

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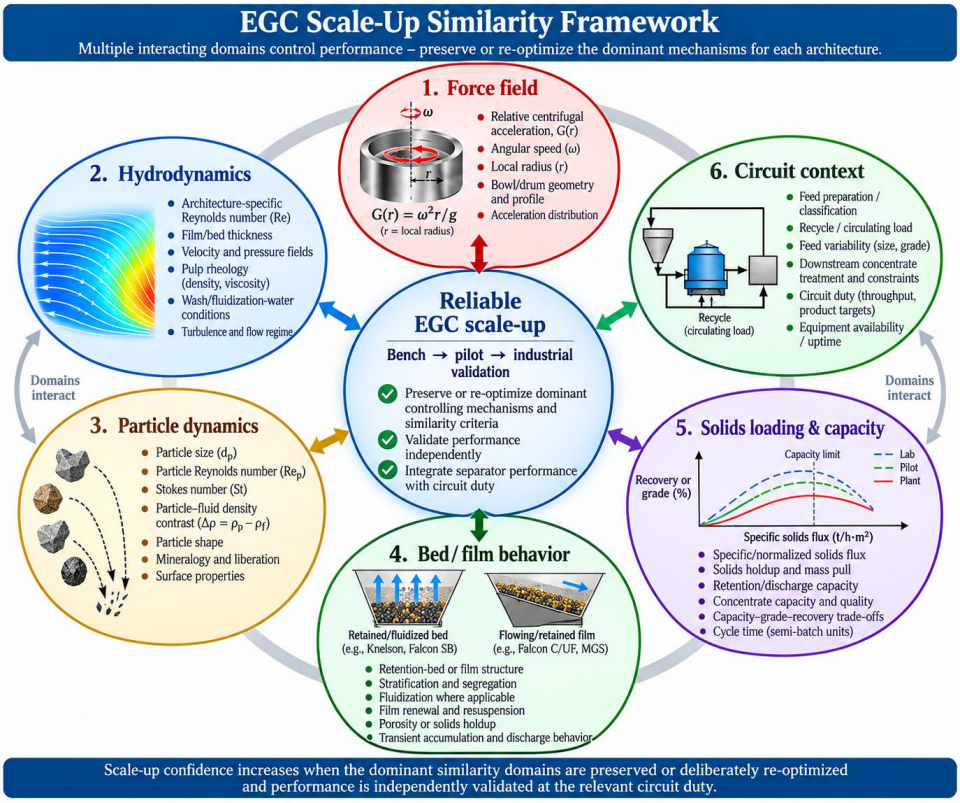
Figure 5. *EGC Scale-Up Similarity Framework: six interacting domains*



Note. Original author-developed conceptual framework developed in this review. It has not yet been prospectively validated as a quantitative or predictive scale-up model. The six domains synthesize the mechanistic and scale-up evidence from the full corpus, with particular support from Chen, Yang, Tong, Niu, et al. (2020), Çerik and Şen (2026), Dehaine et al. (2019), Fatahi and Farzanegan (2018), He et al. (2024), Herman et al. (2022), Rajala (2021), and Sakuhuni et al. (2016, 2022). Architecture-specific descriptors supplement the six common domains.

The framework can be implemented through a staged workflow. First, define the industrial duty: target mineral, feed PSD, liberation state, feed grade and variability, required recovery, allowable mass pull, and circuit location. Second, identify the machine-specific dominant mechanism. Third, identify the dominant similarity constraints and any mutually conflicting requirements. Fourth, prioritize the constraints most strongly connected to metallurgical performance and select an architecture-specific diagnostic set that includes local G(r), at least one

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hydrodynamic descriptor, at least one particle-response descriptor, and a normalized loading/capacity criterion, supplemented where necessary by pressure-drop/bed-expansion or oscillatory descriptors. Fifth, conduct bench testing over a range broad enough to reveal interactions rather than only a single optimum. Sixth, deliberately re-optimize domains that cannot be preserved exactly. Seventh, validate the resulting model or operating rule at an intermediate or independent scale. Eighth, close the scale-up with a plant mass balance that includes classification, recycle, availability, downstream concentrate recovery, installed power/torque, specific energy, process-water demand, and mechanical operating constraints.

Table 7 converts the framework into research priorities and minimum validation requirements. A central gap is the scarcity of studies reporting complete geometric, hydrodynamic, bed/film-state, and loading metadata across two or more sizes of the same EGC architecture. Without such data, the literature can demonstrate sensitivity but cannot establish robust inter-scale correlations. Additional gaps include limited active-zone RTD reporting, insufficient measurement of film thickness and retained-mass or holdup saturation, inconsistent normalization of solids flux and capacity, and weak integration between mineralogical characterization and scale-up modeling. Addressing these gaps would allow future studies to distinguish machine-specific empirical tuning from transferable scale-up relationships.

Table 7. Research gaps and minimum validation requirements for industrial EGC scale-up

Research gap	Why it matters	Minimum future reporting/validation
Multi-size experiments on the same architecture	Direct similarity relationships cannot be separated cleanly from ore effects	At least two geometrically distinct sizes with matched feed and replicated settings
Local hydrodynamic and bed/film-state measurements	Nominal G hides velocity, pressure, film/bed structure, water-delivery, and holdup differences	Velocity/pressure and film/bed-state measurements or validated CFD fields plus architecture-specific Re-type groups
RTD in active separation zones	Residence controls capture opportunity and resuspension	Tracer RTD or validated active-zone residence distribution

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Research gap	Why it matters	Minimum future reporting/validation
Capacity, loading, and saturation reporting	Bench cycles may operate far below industrial solids loading or discharge duty	Retained mass/holdup versus time, specific solids flux, mass pull, and retention/discharge capacity
Mineralogy-linked partition functions	Bulk recovery masks liberation, density, and shape effects	Size-by-size mineralogy, density/shape classes, and multidimensional recovery
Independent-scale model validation	High laboratory R^2 does not demonstrate transferability	Hold-out ore domain and at least one independent pilot or plant validation
Circuit and availability closure	Industrial recovery includes uptime, recycle, and downstream losses	Full mass balance, availability, recycle PSD, and concentrate-treatment extraction

Note. This review proposes the requirements from the combined evidence base. They are intended as minimum reporting and validation targets for future scale-up studies, not as universal similarity conditions that must all be satisfied simultaneously.

12. Conclusions and Research Priorities

Enhanced gravity concentrators cannot be scaled reliably by preserving nominal G alone. Nominal G describes imposed centrifugal intensity, but transfer to larger equipment also changes geometry-dependent acceleration fields, hydrodynamics, particle response, bed/film structure, solids loading, residence behavior, retention or discharge capacity, and circuit duty. The dominant balances differ among Knelson, Falcon SB, Falcon C, Falcon UF, and MGS architectures; the evidence synthesized here does not support a universal single-parameter law. Fixed-geometry optimization must be separated from inter-scale transfer. The most defensible scale-up strategy is to identify the controlling mechanism set, select architecture-specific similarity diagnostics, normalize loading and capacity, test representative mineralogical variability, and validate performance independently at a second scale or in plant duty. Industrial closure must also include availability, classification and recycle, feed variability, and downstream concentrate recovery. Direct controlled multi-size validation within the same EGC architecture remains scarce, so the

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present synthesis should be interpreted as a mechanism-based framework for designing and auditing scale-up rather than as a validated universal correlation.

The proposed author-developed six-domain EGC Scale-Up Similarity Framework—force field, hydrodynamics, particle dynamics, bed/film behavior, solids loading and capacity, and circuit context—provides a practical structure for test-work design, model review, and industrial translation, but it has not yet been prospectively validated as a predictive scale-up model. Future research should prioritize controlled multi-size experiments on the same architecture with matched feed mineralogy, local velocity/pressure and film or bed-state measurements, active-zone RTD characterization, standardized specific-solids-flux and capacity reporting, replicate variability and uncertainty reporting, mineralogy-linked partition functions, mechanical/energy feasibility data, and open pilot-to-plant validation datasets. Such work would move EGC engineering from machine-specific empirical tuning toward transferable, falsifiable, and explicitly bounded scale-up relationships.

Declarations

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Conflict of Interest

The author declares no conflict of interest.

Data Availability

No new experimental datasets were generated. All quantitative values discussed in the review are traceable to the cited literature.

Author Contributions

Conceptualization, methodology, critical analysis, literature synthesis, visualization, and writing—original draft and review/editing: Author.

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