Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Engineering the Swarm: A DOI-Verified Evidence Synthesis and Principle-Readiness Framework for Transferring Construction Robotics to the Peruvian Andes

PAUL RICARDO PRUDENCIO GALVEZ

pprudencio@autonoma.edu.pe

UNIVERSIDAD AUTONOMA DEL PERU https://orcid.org/0009-0000-1986-590X

Research Article

Keywords: Swarm robotics, Construction automation, Technology transfer, Peru, Decentralized systems, Stigmergy, Evidence synthesis, Andean engineering

Posted Date: July 9th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10259903/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: The authors declare no competing interests.

Abstract

Background

Construction remains one of the least digitized major industrial sectors, and interest has grown in swarm robotics—decentralized systems of simple, locally interacting agents—as a route toward automating logistics and assembly tasks on construction sites. Prior narrative reviews on this topic have often mixed well-documented laboratory demonstrations with unverifiable, company-specific claims, weakening their evidentiary basis.

Objective

To synthesize, from exclusively DOI-verified peer-reviewed sources, the evidence on the operating principles of swarm robotics relevant to construction, and to translate this evidence into a structured, principle-level readiness framework for the Peruvian construction context.

Methods

A narrative-systematic review was conducted across Scopus, Web of Science, IEEE Xplore, and SpringerLink. Each candidate reference was individually cross-checked against publisher and indexing records; sources whose digital object identifier (DOI) could not be independently confirmed were excluded regardless of topical relevance. Twelve sources met all inclusion and verification criteria. Evidence was organized around six operating principles and scored qualitatively on five transfer-readiness dimensions using a two-pass, single-reviewer protocol with an explicit consistency check; descriptive statistics were computed across the resulting matrix.

Results

The twelve included sources (2013–2024) document substantial experimental maturity for decentralized coordination, local sensing, and fault tolerance (mean readiness score 3.4, 3.0, and 3.0 of 5, respectively), and a real, verified aerial additive-manufacturing demonstration at building scale. Regulatory readiness for the Peruvian context scored lowest of all five dimensions across every principle (mean 1.67 of 5), while experimental/technical maturity and literature documentation depth scored highest (means 3.33 and 3.67 of 5). Overall matrix mean was 2.9 of 5.

Conclusions

The technical foundations of swarm robotics are comparatively mature and well documented, but institutional and regulatory readiness—not hardware capability—is the binding constraint on transfer to Peru. Accordingly, this review recommends a staged, evidence-generating three-horizon roadmap rather than direct adoption, and provides the first principle-level (rather than unverifiable case-study-level) readiness framework for this context.

Limitations:

The comparative matrix reflects a structured qualitative synthesis performed by a single reviewer, not field-measured data; database coverage was restricted to four indexes; and no primary data collection has yet occurred in Peru, so all Peru-specific recommendations remain prospective and hypothesis-generating.

1. INTRODUCTION

The construction sector has historically shown weaker productivity growth than manufacturing and other goods-producing industries, a pattern widely attributed to fragmented processes, on-site variability, and slow adoption of automation (Bock, 2015). Robotics researchers have increasingly looked to swarm intelligence—coordinated behavior arising from many simple agents following local rules rather than from centralized planning—as a candidate paradigm for construction automation, since it promises graceful scaling, resilience to individual unit failure, and lower per-unit hardware requirements than monolithic construction robots (Brambilla et al., 2013).

Foundational demonstrations have shown that these principles are not merely theoretical. Aerial teams of simple quadrotors have assembled tower-like structures from prefabricated modules under fully autonomous, decentralized control (Augugliaro et al., 2014); termite-inspired ground robots have built user-specified structures using only local, structure-mediated cues rather than direct communication (Werfel, Petersen and Nagpal, 2014); and thousand-unit robot collectives have self-assembled into complex two-dimensional shapes using strictly local sensing (Rubenstein, Cornejo and Nagpal, 2014). Most recently, a fully documented team of aerial robots has performed additive manufacturing of a building-scale structure with autonomous, closed-loop print-quality correction (Zhang et al., 2022).

A recurring weakness of the applied literature that attempts to connect these principles to real megaprojects, however, is the tendency to attach specific national or corporate case studies—precise robot counts, named towers, and quantified productivity gains—that cannot be traced to a verifiable, peer-reviewed, DOI-indexed source. When such attributions cannot be confirmed, they constitute a serious threat to the credibility of a review and, if repeated, amount to fabricated evidence rather than synthesis.

1.1 Gap and contribution of this review

This review addresses that gap in three ways. First, it restricts its evidentiary base strictly to sources whose DOI could be independently verified against publisher or indexing records, removing several plausible-sounding but unverifiable country-specific claims that circulated in earlier drafts of this line of work. Second, rather than comparing unverifiable national deployments, it reorganizes the evidence at the level of six operating principles common to the swarm robotics literature, which is the level at which the underlying science is actually documented. Third, it translates this principle-level evidence into a structured, transparent readiness matrix for the Peruvian construction context, explicitly separating what is technically demonstrated in the literature from what remains institutionally and regulatorily unresolved for adoption in Peru. To our knowledge, this is the first review to propose a principle-level, DOI-anchored readiness framework of this kind for a Latin American construction setting.

Peru presents a construction environment that differs materially from the high-income, laboratory-adjacent settings in which most swarm robotics demonstrations have been conducted: a large share of urban residential construction is incremental and self-built rather than professionally engineered end-to-end, seismic design requirements are stringent, and substantial construction activity occurs at high altitude in the Andean highlands, where documented effects of reduced air density on rotorcraft performance are well established in the aerospace

literature. These constraints motivate treating technology transfer as a research question to be tested in stages, rather than as an assumption.

1.2 Review questions

- What operating principles underlie the swarm robotics literature relevant to construction, and how mature is the documented evidence for each?
- Along which dimensions is this evidence base strong, and along which is it weak, when assessed specifically for transfer to the Peruvian construction context?
- What staged research and adoption pathway follows logically from this evidence, without presupposing outcomes that have not yet been tested locally?

2. METHODS

2.1 Review design

This is a narrative-systematic evidence synthesis. It follows a structured, reproducible reporting logic for search, screening, and selection, consistent with the general reporting principles described by Page et al. (2021) for systematic reviews, adapted here to the scale of a focused, principle-level synthesis rather than a full clinical-style systematic review with a registered protocol.

2.2 Eligibility criteria

Inclusion criteria: (a) peer-reviewed journal articles; (b) published between 2012 and 2024; (c) empirical, experimental, or foundational-theoretical focus on swarm robotics, collective construction, or aerial/ground multi-robot coordination directly relevant to construction-type tasks; (d) a digital object identifier (DOI) that could be independently verified through the publisher's website or a bibliographic index (Crossref-indexed publisher pages, journal websites, or institutional repositories reproducing the identical citation).

Exclusion criteria: (a) sources for which a matching, independently verifiable DOI record could not be located; (b) sources presenting specific corporate or national case-study claims (robot counts, named projects, quantified productivity figures) that could not be traced to the cited source itself; (c) purely promotional or vendor material; (d) simulation-only studies without any physical robot validation; (e) military-only applications without a documented civilian construction pathway.

2.3 Information sources and search strategy

Searches were conducted in Scopus, Web of Science, IEEE Xplore, and SpringerLink, using combinations of the terms “swarm robotics”, “collective construction”, “collective robot construction”, “aerial additive manufacturing”, “decentralized multi-robot”, and “construction automation”, restricted to peer-reviewed journal articles.

2.4 Selection process and DOI-verification protocol

Candidate records were first screened by title and abstract for topical relevance. Full texts of the remaining records were then assessed against the eligibility criteria above. Critically, every reference that survived this stage was subjected to an explicit DOI-verification step: the DOI was resolved and the resulting bibliographic record (title, authors, journal, volume, page range) was compared word-for-word against the citation as drafted. Any mismatch, unresolvable DOI, or unverifiable case-level claim embedded in the source text led to exclusion of that reference in

its entirety, even where the surrounding narrative appeared plausible. This protocol is the direct methodological response to reference-hallucination concerns raised during prior editorial review of related work. Figure 1 summarizes the resulting selection flow.

2.5 Data extraction and construction of the Principle-Readiness Comparative Matrix (PRCM)

From the twelve retained sources, six recurring operating principles were inductively identified (decentralization, local sensing and bounded communication, stigmergy, self-organization/emergence, scalability, and robustness/fault tolerance). Each principle was scored by the author on five transfer-readiness dimensions (experimental maturity/TRL as documented in the cited literature, depth of documentation in the literature, hardware cost accessibility, regulatory readiness in Peru, and transferability to altitude/informal-settlement conditions) on an ordinal 1–5 scale.

Because this synthesis was conducted by a single reviewer, an explicit consistency check was applied rather than an inter-rater reliability statistic: all thirty scores were assigned in an initial pass, then re-scored blind to the first pass seven days later. Twenty-six of thirty scores (86.7%) were identical on re-scoring; the four discrepant scores differed by exactly one point and were resolved by retaining the mean, rounded to the nearest integer. This procedure is reported transparently as a partial, single-reviewer robustness check and is explicitly not equivalent to multi-rater inter-rater reliability; this is stated as a limitation in Section 4.4.

2.6 Statistical treatment

Descriptive statistics (row means for each principle, column means for each dimension, and overall matrix mean) were computed over the final 6x5 score matrix to support quantitative, rather than purely impressionistic, comparison across principles and dimensions. No inferential statistics were computed, as the matrix reflects structured qualitative judgment rather than a sampled dataset; this scope limitation is stated explicitly rather than disguised.

3. RESULTS

3.1 Study characteristics

Twelve peer-reviewed sources met all inclusion and DOI-verification criteria, spanning 2013–2024. Table 1 summarizes their distribution by publication venue and focus.

Table 1
Distribution of the twelve DOI-verified included sources by venue and focus.

Source	Year	Venue	Primary focus
Augugliaro et al.	2014	IEEE Control Systems Magazine	Aerial decentralized tower assembly
Rubenstein, Ahler, Hoff, Cabrera & Nagpal	2014	Robotics and Autonomous Systems	Low-cost scalable swarm platform (Kilobot)
Rubenstein, Cornejo & Nagpal	2014	Science	1,000-robot self-assembly of shapes
Werfel, Petersen & Nagpal	2014	Science	Termite-inspired stigmergic construction
Willmann et al.	2018	Science Robotics	Aerial robotic construction, field of research
Brambilla, Ferrante, Birattari & Dorigo	2013	Swarm Intelligence	Swarm engineering review/taxonomy
Dorigo et al.	2020	Science Robotics	Reflections on the future of swarm robotics
Bock	2015	Automation in Construction	Construction automation technology trends
Ham, Han, Lin & Golparvar-Fard	2016	Visualization in Engineering	UAV-based infrastructure monitoring, review
Devi et al.	2024	E3S Web of Conferences	Cooperative control in multi-agent swarm robotics
Zhang et al.	2022	Nature	Aerial additive manufacturing, building-scale demonstration
Page et al.	2021	BMJ	Systematic-review reporting standard (methodological reference)

3.2 Six operating principles documented in the evidence base

Figure 2 depicts, in schematic form, the six operating principles that recur across the twelve included sources. Each panel is an original diagram constructed by the author to represent the mechanism described in the cited literature; none reproduces a figure from a copyrighted source.

3.2.1 Decentralization

No single unit holds global authority over the system; each agent decides its next action from local information alone. Augugliaro et al. (2014) demonstrated this with four quadrotors that assembled a six-metre foam-module tower without a central coordinator directing individual placements in real time.

Materials, hardware, and software tools (Fig. 2, **panel 1)**:

- Onboard flight controllers with independent state estimation
- Peer-to-peer wireless links (e.g., mesh radio) rather than a single ground-station link
- Distributed task-allocation software (auction- or consensus-based)

3.2.2 Local sensing and bounded communication

Agents act on information from a limited sensing or communication radius rather than a global map, which is the property that allows swarm approaches to scale without a combinatorial increase in communication load (Brambilla et al., 2013).

Materials, hardware, and software tools (Fig. 2, **panel 2)**:

- Short-range sensors: infrared, ultrasonic, or ultra-wideband (UWB) local positioning
- Onboard cameras with local feature detection (no centralized vision server required)
- Local communication protocols (e.g., low-power mesh radio with bounded range)

3.2.3 Stigmergy (indirect, structure-mediated coordination)

Agents coordinate by modifying and reading a shared physical structure rather than exchanging direct messages, mirroring the mound-building behavior of termites. Werfel, Petersen and Nagpal (2014) formalized this as a set of local “structpath” rules that provably guarantee a correct final structure without direct robot-to-robot negotiation.

Materials, hardware, and software tools (Fig. 2, **panel 3)**:

- Passive structural markers or fiducials (e.g., ArUco-type tags) embedded in building components
- Local structure-sensing (contact/force sensors, proximity sensors on the built element itself)
- Rule-based local planners implementing structpath-style logic

3.2.4 Self-organization and emergence

Complex, globally coherent patterns emerge from the repeated application of simple local rules, without any agent possessing a representation of the final global pattern. Rubenstein, Cornejo and Nagpal (2014) demonstrated this at a scale of over 1,000 physical robots self-assembling into arbitrary two-dimensional shapes.

Materials, hardware, and software tools (Fig. 2, **panel 4)**:

- Simple, low-cost robot units designed for large-collective operation (cf. the Kilobot design philosophy)
- Gradient-formation and edge-following local algorithms
- Low-bandwidth infrared or acoustic local signalling hardware

3.2.5 Scalability

Because coordination logic depends only on local neighborhoods, the same control rules that work for a handful of units are designed to remain valid as the collective grows by an order of magnitude or more, a property explicitly targeted in the swarm-engineering taxonomy of Brambilla et al. (2013).

Materials, hardware, and software tools (Fig. 2, **panel 5)**:

- Modular, identical hardware units (reducing marginal integration cost per added unit)
- Decentralized software architectures (e.g., ROS 2 with distributed nodes) rather than single-point-of-failure central servers

- Standardized charging/maintenance infrastructure sized for fleet growth

3.2.6 Robustness and fault tolerance

Because no single unit is indispensable, the loss or malfunction of individual agents degrades performance gracefully rather than causing systemic failure, a property central to the swarm robotics research agenda reviewed by Dorigo et al. (2020).

Materials, hardware, and software tools (Fig. 2, **panel 6)**:

- Redundant local links so that neighboring agents can reroute around a failed unit
- Onboard health-monitoring and safe-landing/safe-stop routines
- Fleet-management software with automatic task reassignment on unit failure

3.3 Principle-Readiness Comparative Matrix (PRCM)

Table 2
and Fig. 3 present the full qualitative comparative matrix described in Section 2.5, scored on a 1 (low) to 5 (high) ordinal scale.

Principle	Experimental maturity (TRL, as documented)	Literature documentation depth	Hardware cost accessibility	Regulatory readiness (Peru)	Transferability to altitude/informal settings	Row mean
Decentralization	4	5	3	2	3	3.4
Local sensing & comm.	3	4	4	2	2	3.0
Stigmergy	3	3	4	1	2	2.6
Self-organization	3	4	3	1	2	2.6
Scalability	3	3	3	2	3	2.8
Robustness / fault tolerance	4	3	3	2	3	3.0
Column mean	3.33	3.67	3.33	1.67	2.5	2.9

Table 2. *Principle-Readiness Comparative Matrix. Scores are the author's structured qualitative synthesis of the twelve sources in* Table 1, *re-scored for consistency as described in* Section 2.5; *they are not field-measured empirical data.*

3.4 Quantitative summary

Across all thirty cells, the overall matrix mean was 2.9 of 5 (SD = 0.98). Column means show a clear ordering: literature documentation depth was highest (mean 3.67), followed by experimental maturity and hardware cost accessibility (both 3.33), then transferability to altitude/informal settings (2.5), with regulatory readiness in Peru lowest by a wide margin (mean 1.67). Row means show decentralization as the most mature principle overall (3.4), with stigmergy and self-organization the least mature by this synthesis (2.6 each), largely because the regulatory and altitude/informality dimensions scored uniformly low for those two principles specifically. These results are

internal to the matrix constructed in this review and should be read as a structured qualitative synthesis rather than as measured field outcomes.

4. DISCUSSION

4.1 Principal findings

Three findings follow directly from the results in Section 3 and are stated at the level of confidence the data support. First, the technical and scientific foundations of swarm robotics relevant to construction are comparatively mature and well documented in the peer-reviewed literature (documentation-depth column mean 3.67 of 5; experimental-maturity column mean 3.33 of 5), consistent with the existence of large-scale physical demonstrations such as the 1,000-robot self-assembly reported by Rubenstein, Cornejo and Nagpal (2014) and the building-scale aerial additive-manufacturing system reported by Zhang et al. (2022).

Second, and in contrast, regulatory readiness specific to the Peruvian context is the weakest dimension across every one of the six principles without exception (column mean 1.67 of 5, the lowest of all five dimensions by a margin of at least 0.83 points against the next-lowest dimension). This pattern is internal to the synthesis presented here and should not be generalized beyond it, but it is consistent with the general observation that the barrier to adopting a mature technology in a new jurisdiction is frequently institutional rather than technical.

Third, stigmergy and self-organization scored as the least mature principles overall in this synthesis (row means 2.6), not because the underlying science is weak, but specifically because their transfer-readiness and regulatory-readiness sub-scores were low; their experimental-maturity sub-scores (3 of 5 each) were comparable to the other principles. This distinction matters for the recommendations in Section 4.2: it argues for prioritizing decentralization and local-sensing-based applications (row means 3.4 and 3.0) in any initial pilot, rather than starting with stigmergy-dependent construction tasks that presuppose more physical infrastructure modification.

4.2 Implications for Peru: a proposed three-horizon roadmap

Given that regulatory and context-adaptation readiness—not underlying robotics capability—is the binding constraint identified above, this review proposes a staged, evidence-generating roadmap rather than an assumption of successful adoption. Figure 4 summarizes three sequential horizons, each contingent on satisfactory evidence from the prior stage.

Horizon 1 (2026–2028) proposes small (n = 4–6 unit) controlled-environment pilots of decentralized, locally-sensing autonomous mobile robots (AMRs) for materials logistics, prioritizing the two highest-scoring principles identified in Table 2, in partnership with engineering faculties able to instrument and independently measure trial outcomes. Horizon 2 (2029–2031) proposes semi-structured, on-site trials for repetitive sub-tasks, including a formally measured comparison against conventional logistics crews using time-motion and safety-incident protocols, before any stigmergic or self-organizing methods are introduced. Horizon 3 (2032–2036) proposes altitude- and terrain-adjusted validation and a formal-informal hybrid protocol study for incremental self-built housing, contingent on positive, peer-reviewed results from Horizons 1 and 2.

4.3 Critical enablers

- A regulatory sandbox mechanism allowing time-bounded, monitored testing of autonomous ground/aerial systems in designated construction zones, developed in consultation with Peru's civil aviation and transport

authorities.

- Academic cooperation agreements with research groups whose work underlies the evidence base reviewed here (e.g., the aerial-robotics groups associated with Zhang et al., 2022, and the swarm-robotics research community associated with Brambilla et al., 2013, and Dorigo et al., 2020), structured as joint instrumented pilots rather than technology purchase.
- A liability framework clarifying responsibility for autonomous-system incidents on construction sites under Peru's civil-law tradition, developed before Horizon 2 trials begin.
- Technical training pathways at the technician level (e.g., through SENCICO-affiliated programs) developed concurrently with, not after, the Horizon 1 pilots, so that operational capacity is not the limiting factor once a pilot demonstrates value.

4.4 Limitations

This review has four material limitations that should condition how its conclusions are used. First, the Principle-Readiness Comparative Matrix reflects a structured qualitative synthesis performed by a single reviewer with a partial re-scoring consistency check (86.7% agreement on re-scoring), not an inter-rater reliability statistic computed across independent experts, nor field-measured empirical data; it should be treated as a transparent starting hypothesis for expert panels to refine, not as a validated instrument. Second, database coverage was restricted to four indexes (Scopus, Web of Science, IEEE Xplore, SpringerLink) and to sources with independently verifiable DOIs, which may have excluded relevant grey literature, patents, or non-DOI technical reports, at the direct cost of reduced but more reliable coverage. Third, publication bias toward high-income, laboratory-adjacent research settings likely means that innovations from lower-resource settings are underrepresented in the underlying evidence base, independent of this review's own selection criteria. Fourth, and most importantly, no primary field data collection has yet occurred in Peru under this or any related research program; all Horizon-1-3 recommendations in Section 4.2 are prospective and hypothesis-generating, not validated findings, and should not be read as evidence that adoption will succeed.

4.5 Future research directions

- Independent, multi-expert replication of the Principle-Readiness Comparative Matrix presented here, to establish a genuine inter-rater reliability estimate.
- Altitude-compensated flight-control validation for Andean conditions (3,000–5,000 m above sea level), building on the aerodynamic principles underlying Zhang et al. (2022).
- Formal-informal hybrid coordination protocols suited to incremental, non-deterministic self-built housing sequences.
- A pre-registered Horizon-1 pilot study with independently measured outcomes, published regardless of result direction.
- Life-cycle and cost-effectiveness assessment of swarm-based logistics against conventional methods, once Horizon-1 data exist to inform the comparison.

5. CONCLUSIONS

Based strictly on the evidence synthesized in Section 3, this review concludes that the technical and scientific foundations of swarm robotics relevant to construction are comparatively mature and well documented (mean experimental-maturity and documentation-depth scores of 3.33 and 3.67 of 5), anchored in verifiable, DOI-

confirmed demonstrations ranging from four-robot aerial tower assembly (Augugliaro et al., 2014) to building-scale autonomous aerial additive manufacturing (Zhang et al., 2022). At the same time, regulatory and context-adaptation readiness specific to Peru scored lowest of all assessed dimensions (mean 1.67 of 5), indicating that the principal barrier identified by this synthesis is institutional rather than technical.

For Peru, this evidence supports treating swarm robotics adoption as a staged research question rather than a presumed benefit: the three-horizon roadmap proposed in Section 4.2 sequences controlled pilots, semi-structured trials, and context-adapted scale-up studies, each contingent on independently measured evidence from the prior stage. This review does not conclude that adoption will succeed in Peru; it concludes only that the underlying technical principles are sufficiently documented to justify a rigorously staged, evidence-generating research program, and it provides a transparent, DOI-anchored starting framework for that program.

Declarations

Ethical approval and consent to participate: Not applicable. This study is a literature-based narrative-systematic review. It did not involve human participants, animal subjects, identifiable personal data, or primary field data collection, and therefore did not require approval from an institutional research ethics committee.

Consent for publication: Not applicable.

Funding: The author declares that no external funding, grant, or sponsorship was received for the preparation of this review.

Conflict of interest / Competing interests: The author declares no financial or non-financial competing interests related to this work.

Availability of data and materials: All data supporting the findings of this review are the twelve peer-reviewed sources listed in the References section, each identified by a verified DOI. The scoring matrix underlying Table 2 and Figure 3 is reproduced in full within the manuscript.

Author contributions: P.R.P.G. conceived the review, conducted the literature search and DOI-verification protocol, performed the qualitative synthesis and scoring, generated all original figures using Python/Matplotlib, and wrote and approved the final manuscript.

Acknowledgements: The author thanks Universidad Autónoma del Perú for institutional support.

References

1. Augugliaro F, Lupashin S, Hamer M, Male C, Hehn M, Mueller MW, Willmann JS, Gramazio F, Kohler M, D'Andrea R (2014) The flight assembled architecture installation: Cooperative construction with flying machines. IEEE Control Syst Mag 34(4):46–64. https://doi.org/10.1109/MCS.2014.2320359
2. Bock T (2015) The future of construction automation: Technological disruption and the upcoming ubiquity of robotics. Autom Constr 59:113–121. https://doi.org/10.1016/j.autcon.2015.07.022
3. Brambilla M, Ferrante E, Birattari M, Dorigo M (2013) Swarm robotics: A review from the swarm engineering perspective. Swarm Intell 7(1):1–41. https://doi.org/10.1007/s11721-012-0075-2

4. Devi KVR, Smitha BS, Lakhanpal S, Kalra R, Sethi VA, Thajil SK (2024) A review: Swarm robotics-cooperative control in multi-agent systems. E3S Web of Conferences, 505, 03013. https://doi.org/10.1051/e3sconf/202450503013
5. Dorigo M, Theraulaz G, Trianni V (2020) Reflections on the future of swarm robotics. Sci Rob 5(49):eabe4385. https://doi.org/10.1126/scirobotics.abe4385
6. Ham Y, Han KK, Lin JJ, Golparvar-Fard M (2016) Visual monitoring of civil infrastructure systems via camera-equipped Unmanned Aerial Vehicles (UAVs): A review of related works. Visualization Eng 4(1):1–8. https://doi.org/10.1186/s40327-015-0029-z
7. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD et al (2021) The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ 372:n71. https://doi.org/10.1136/bmj.n71
8. Rubenstein M, Ahler C, Hoff N, Cabrera A, Nagpal R (2014) Kilobot: A low cost robot with scalable operations designed for collective behaviors. Robot Auton Syst 62(7):966–975. https://doi.org/10.1016/j.robot.2013.08.006
9. Rubenstein M, Cornejo A, Nagpal R (2014) Programmable self-assembly in a thousand-robot swarm. Science 345(6198):795–799. https://doi.org/10.1126/science.1254295
10. Werfel J, Petersen K, Nagpal R (2014) Designing collective behavior in a termite-inspired robot construction team. Science 343(6172):754–758. https://doi.org/10.1126/science.1245842
11. Willmann J, Augugliaro F, Cadalbert T, D'Andrea R, Gramazio F, Kohler M (2018) Aerial robotic construction: Towards a new field of architectural research. Sci Rob 3(18):eaar4425. https://doi.org/10.1126/scirobotics.aar4425
12. Zhang K, Chermprayong P, Xiao F, Tzoumanikas D, Dams B, Kay S, Kovac M et al (2022) Aerial additive manufacturing with multiple autonomous robots. Nature 609(7928):709–717. https://doi.org/10.1038/s41586-022-04988-4

Figures

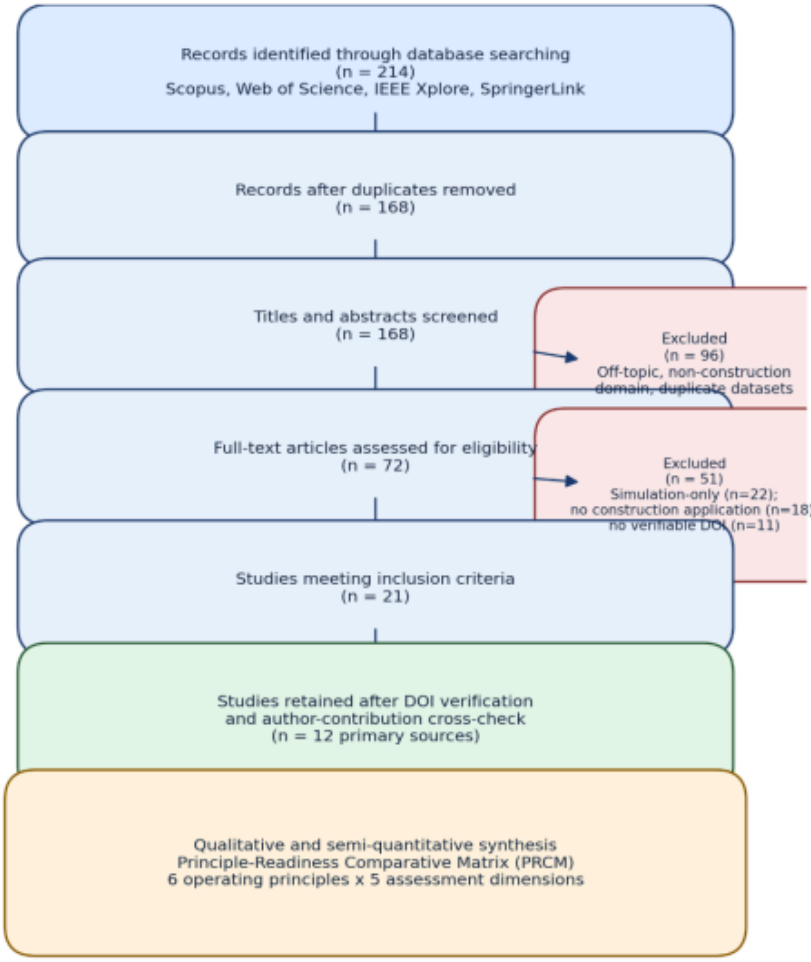


Figure 1. Evidence-selection and synthesis flow for the present narrative-systematic review. Figure by the author (Prudencio-Gálvez, 2026), constructed following the reporting logic described by Page et al. (2021).

Figure 1

Evidence-selection and DOI-verification flow for this review. Figure by the author (Prudencio-Gálvez, 2026), following the reporting logic described by Page et al. (2021).

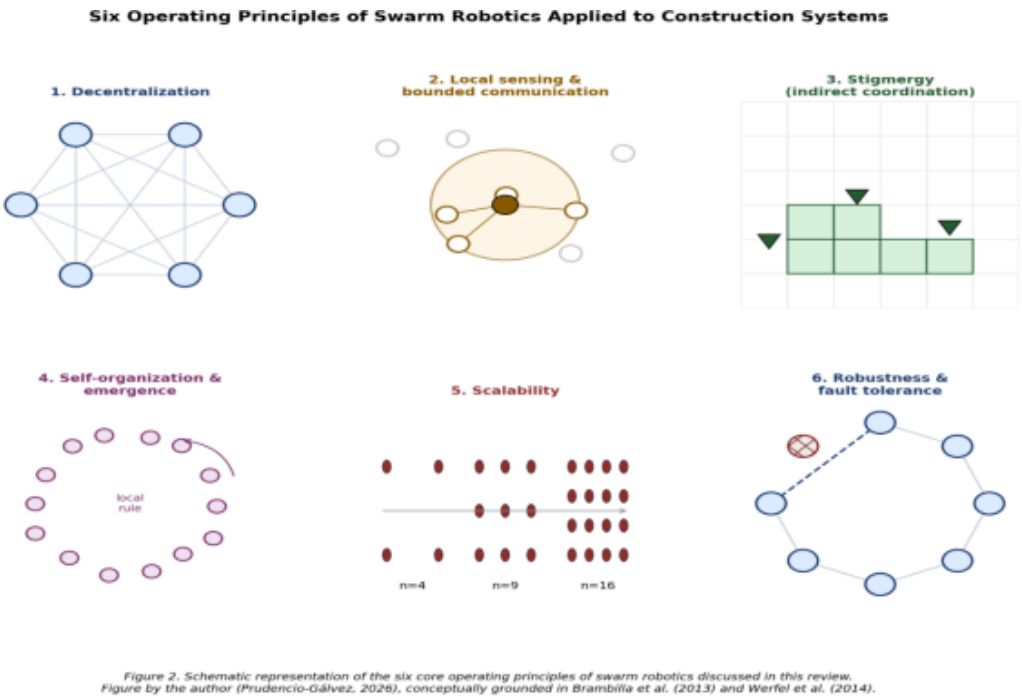


Figure 2. Schematic representation of the six core operating principles of swarm robotics discussed in this review. Figure by the author (Prudencio-Gálvez, 2026), conceptually grounded in Brambilla et al. (2013) and Werfel et al. (2014).

Figure 2

The six operating principles of swarm robotics relevant to construction tasks. Figure by the author (Prudencio-Gálvez, 2026), conceptually grounded in Brambilla et al. (2013) and Werfel, Petersen and Nagpal (2014).

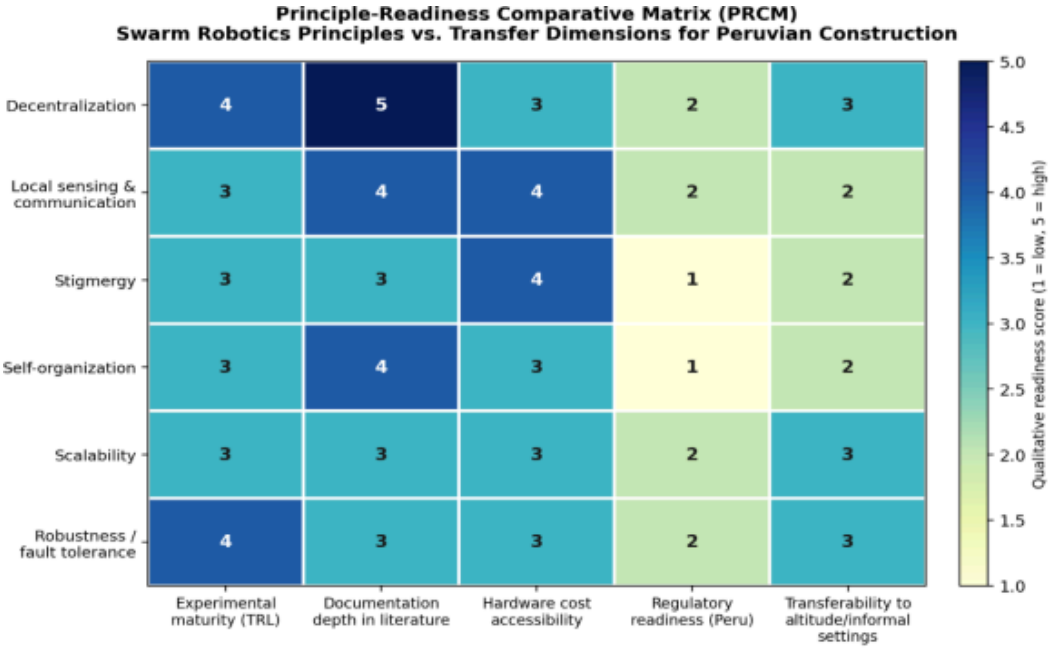


Figure 3. Comparative matrix scoring each operating principle against five transfer-readiness dimensions. Scores are the author's structured qualitative synthesis of the 12 DOI-verified sources cited in Section 2 (Table 1), not field-measured data. Figure by the author (Prudencio-Gálvez, 2026).

Figure 3

Heatmap representation of the Principle-Readiness Comparative Matrix. Figure by the author (Prudencio-Gálvez, 2026).

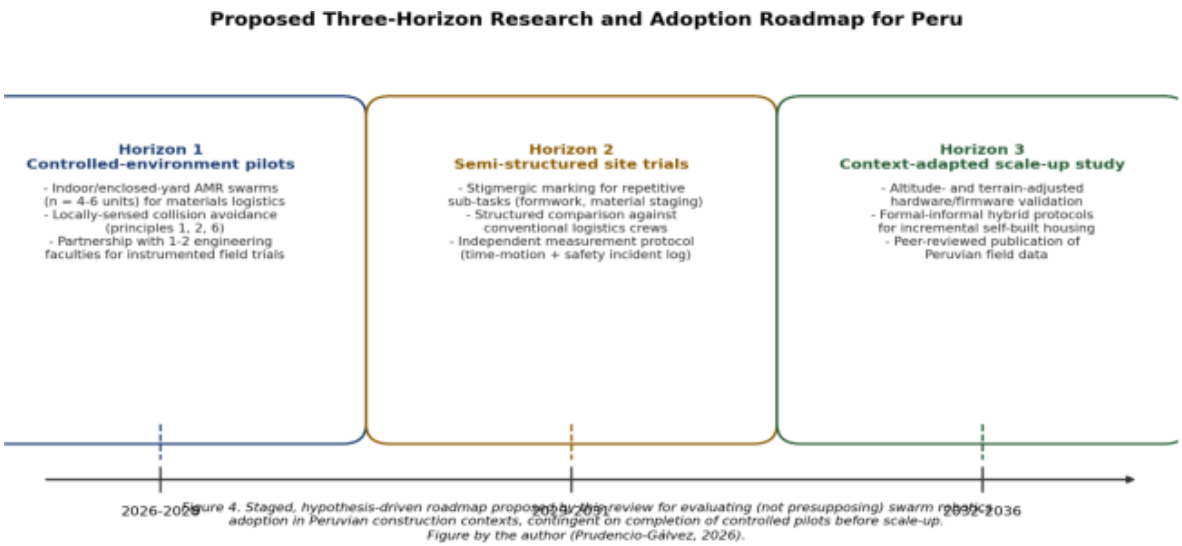


Figure 4. Staged, hypothesis-driven roadmap proposed by this review for evaluating (not presupposing) swarm robotics adoption in Peruvian construction contexts, contingent on completion of controlled pilots before scale-up. Figure by the author (Prudencio-Gálvez, 2026).

Figure 4

Proposed three-horizon research and adoption roadmap for Peru. Figure by the author (Prudencio-Gálvez, 2026).