

A Phased Validation and Rollout Framework for Multi-Site Autonomous Warehouse Robotic Systems: From Single-Site Validation to Network Scale

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Abstract

This paper proposes the Phased Validation and Rollout Framework (PVRF), a phased validation and rollout framework for scaling autonomous robotic systems from a single validated deployment site to a multi-site production network. Multi-site robotic deployment presents qualitatively different challenges from single-site implementation: configuration variability across sites, non-linear incident amplification at scale, and rollback complexity that increases with network size. Existing frameworks from software engineering and manufacturing systems literature do not fully address these challenges in the context of physical-digital robotic systems. The proposed framework organizes the scale-up process into four phases — single-site validation, limited expansion validation, network release, and operational steady state — each with defined scope, success criteria, key risks, and explicit transition conditions. The framework is validated through application to a 26-site deployment of an automated warehouse robotic platform, achieving a 75% reduction in network-wide push-through incidents and zero network-wide outages during the rollout period. A key finding is that the phase transition decision is the highest-leverage management decision in the rollout process.

Keywords

multi-site deployment, phased rollout, warehouse robotics, validation framework, supply chain.

1. Introduction

The deployment of autonomous robotic systems in warehouse environments at network scale — across dozens or hundreds of distribution center sites simultaneously — represents a class of engineering management challenge that is qualitatively distinct from single-site implementation. Yet the literature and practitioner frameworks available to guide this transition are largely drawn from single-site implementation experience or from software engineering contexts that do not account for the physical-digital integration constraints of warehouse robotic systems.

This paper proposes PVRF, a structured framework for managing the transition from single-site validation to multi-site network deployment of autonomous warehouse robotic systems, derived from and validated against the

deployment of an automated robotic platform across 26 distribution center sites in a major North American retail distribution network.

1.1 Objectives

This paper pursues three objectives: (1) to propose a four-phase framework — single-site validation, limited expansion, network release, and operational steady state — with explicit transition conditions between phases; (2) to identify which phase transition carries the highest management leverage over network-scale outcomes; and (3) to validate the framework against a 26-site production deployment, reporting both the outcomes achieved and the limitations of that validation. These objectives are revisited explicitly in the Conclusion.

2. Literature Review

The relevant literature spans warehouse automation system design, manufacturing technology implementation, software staged-rollout practice, and engineering change management. This section reviews each before identifying the gap this paper addresses.

The academic and practitioner literature on warehouse automation has grown substantially in recent years, with comprehensive reviews provided by Fragapane et al. (2021), Boysen et al. (2019), de Koster et al. (2007), Roodbergen and Vis (2009), Tompkins et al. (2010), and Wurman et al. (2008) documenting the operational scale, order-picking design, and automated storage-and-retrieval considerations at play once a robotic platform reaches network scale. This literature focuses primarily on system design, performance modeling, and single-site operations; the specific management challenges of multi-site rollout — configuration heterogeneity, incident amplification, and coordinated change management across a distributed network — receive limited attention.

Research on manufacturing system implementation provides relevant principles for technology adoption at the firm level. Meredith (1987) examines the strategic advantages new manufacturing technology offers small firms, and Grover and Malhotra (1997) provide a tutorial treatment of business process reengineering methodology and evolution. Atieh et al. (2016) document performance improvements from automated warehouse management system implementation specifically. This literature addresses adoption of a technology within a firm, but not the specific dynamics of a platform vendor deploying one system across many client sites simultaneously.

Software engineering literature on continuous delivery and staged rollout offers structural parallels. Humble and Farley (2010) and Kim et al. (2016) describe staged deployment and gating practices that inform the phase-transition structure proposed in this paper, but assume software-only systems where physical configuration variability across deployment targets is absent. The engineering change management literature — Jarratt et al. (2011) and Reddi and Moon (2009) — addresses how changes propagate across interdependent components and how that propagation should be governed, a concern structurally related to the incident-amplification risk this paper addresses, though developed in the context of product design change rather than post-deployment network scale-up.

Taken together, existing literature documents warehouse system design at scale, firm-level technology adoption, software staged-rollout practice, and change propagation governance — but no prior work integrates these into a phased framework, with explicit transition conditions, for scaling a single robotic platform from one validated site to a live multi-site production network. This paper addresses that gap.

3. Methods

Multi-site robotic deployment introduces risks that are absent or qualitatively different from single-site deployment: configuration heterogeneity across facility layout, product mix, and environmental conditions; incident amplification, where a defect rate manageable at single-site scale is multiplied across an N-site network; rollback complexity, which scales non-linearly rather than proportionally with network size; and operational dependency, since at network scale client operations depend on the robotic system, and extended outages carry commercial consequences absent in pilot deployments.

The proposed framework organizes the multi-site deployment process into four phases with explicit transition conditions, illustrated in Figure 1.



Figure 1. Phased validation and rollout framework: four-phase structure with explicit gate transitions.

Phase 1 — Single-Site Validation establishes a production-validated baseline at a site representative of the network's configuration profile. Success criteria: all safety, performance, and reliability KPIs met under full production load, no unresolved P0/P1 defects, rollback procedure demonstrated. Transition condition: formal sign-off by engineering, safety, and operations leads.

Phase 2 — Limited Expansion Validation expands to a small set of sites selected specifically for configuration diversity, to surface configuration-specific issues at manageable scale before network release. Transition condition: a minimum of two weeks of stable production operation at all expansion sites with no unresolved P1-or-higher defects.

Phase 3 — Network Release deploys the system across the full network in sequential batches, with monitoring gates between batches; batch size is calibrated against incident amplification risk. Transition condition: incident rates stable across all deployed sites, no active P0/P1 issues, operational teams trained.

Phase 4 — Operational Steady State is not a deployment phase but an ongoing operational posture, dependent on a structured change management process. Its key risk is the accumulation of undocumented, individually benign site-specific changes that collectively degrade network-level performance.

4. Data Collection

The framework was applied during the expansion of an automated warehouse robotic platform to 26 distribution center sites across a major North American retail distribution network. The platform includes integrated vision-based detection systems (Menezes 2026a) managed through MSRMF, a gate-based release management framework (Menezes 2026b), that provided the Phase 4 change management structure. Phase execution was tracked against each phase's defined success criteria and transition conditions, and quantitative outcomes — incident rates, outage counts,

and sites reaching steady state — were collected from the platform's operational monitoring system across the full rollout period.

5. Results and Discussion

5.1 Numerical Results

Table 1 presents the key observations and outcomes by framework phase

Table 1. Key observations and outcomes by framework phase

Phase	Key Observation	Outcome
Phase 1	Validation site selected as mid-complexity facility; proved representative of network median configuration	No critical issues in Phase 2 attributable to Phase 1 validation gaps
Phase 2	Two configuration issues surfaced that were not present at the Phase 1 site; both resolved before the Gate 2 decision	Issues addressed at limited scale rather than network scale
Phase 3	Batches of approximately 5 sites with 1-week monitoring intervals; gate-based release framework provided change control	Zero network-wide outages during rollout
Phase 4	Ongoing operations with structured release management; incident rates sustained at post-rollout baseline	75% network-wide incident reduction sustained

5.2 Graphical Results

Figure 2 presents the three headline quantitative outcomes of the framework application: a 75% network-wide push-through incident reduction from pre-framework baseline, zero network-wide outages during the Phase 3 rollout, and all 26 sites successfully reaching Phase 4 operational steady state.

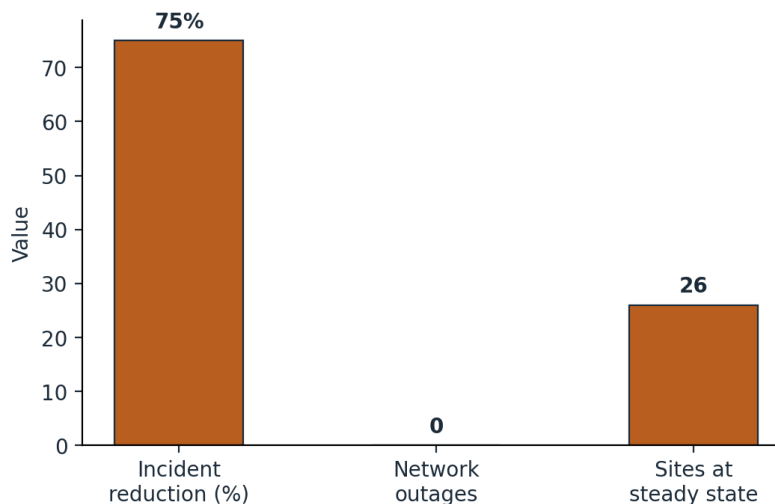


Figure 2. Quantitative rollout outcomes: incident reduction, network outages, and sites reaching operational steady state.

5.3 Proposed Improvements

The most significant finding from the framework application is that the Gate 2 decision — whether to proceed from limited expansion to network release — is the highest-leverage management decision in the multi-site rollout process. The two configuration issues identified in Phase 2 illustrate why: at Phase 1 scale, they were invisible; modeling their incident rate across the full 26-site network indicated a potential for dozens of additional incidents per week at network scale, an amplification the Phase 2 gate prevented entirely.

This finding motivates a concrete process improvement for practitioners: build explicit phase-transition criteria into the project plan before deployment begins, rather than evaluating readiness under commercial timeline pressure. Commercial pressure frequently creates incentive to compress Phase 2 duration or proceed to network release before the monitoring period has elapsed; the framework provides a structured, pre-committed basis for resisting that pressure, consistent with the change-propagation literature's finding that governance structure, not technical content, is typically the binding constraint on safe change velocity (Jarratt et al. 2011; Reddi and Moon 2009).

5.4 Validation

The framework was validated against a single 26-site production deployment, described in Section 4. The framework assumes the existence of a structured change management process in Phase 3 and Phase 4; in the deployment described here, this was provided by MSRMF, the gate-based release management framework described in related work (Menezes 2026b). Practitioners implementing the phased rollout framework without a concurrent change management framework would be expected to find the Phase 3 and Phase 4 transition conditions difficult to sustain, since the absence of structured change control progressively degrades the validated performance baseline — though this specific counterfactual was not tested directly in this deployment.

This paper presents findings from a single deployment context; the specific phase durations, batch sizes, and monitoring periods described reflect the characteristics of that context, and practitioners applying the framework should adapt these parameters to their own deployment scale, platform architecture, and risk tolerance while preserving the underlying structure of explicit phase transitions with defined criteria. The framework is expected to generalize to other autonomous system deployments in distribution environments — including autonomous mobile robots (AMRs) and automated storage and retrieval systems (AS/RS) — where similar scale-up dynamics apply, consistent with the operational patterns documented across that literature (Fragapane et al. 2021; Roodbergen and Vis 2009). Extension to highly regulated environments (pharmaceutical, food safety) would require additional documentation and validation requirements at each gate.

6. Conclusion

This paper proposed PVRF, a four-phase validation and rollout framework for managing the transition from single-site validation to multi-site network deployment of autonomous warehouse robotic systems. Returning to the three objectives stated in Section 1.1: the four-phase framework, with explicit transition conditions, was presented in full (Objective 1); the Gate 2 transition — from limited expansion to network release — was identified as the highest-leverage management decision in the process (Objective 2); and the framework was validated against a 26-site production deployment, achieving a 75% reduction in network-wide push-through incidents and zero network-wide outages, with the single-deployment scope of that validation stated explicitly (Objective 3).

The central practical recommendation for multi-site deployment practitioners is to treat the Gate 2 phase transition decision as the highest-leverage management choice in the process, and to build explicit transition criteria into the project plan before deployment begins rather than evaluating readiness under commercial timeline pressure.

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Biographies

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