A Systems Engineering Framework for Adapting General-Purpose Service Robots for Construction Project Operations

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Abstract –

Construction project operations remain difficult to automate due to dynamic site conditions, limited workflow standardization, and the absence of adaptable robotic platforms. General-purpose service robots (GPSRs), while mature in navigation, sensing, and data acquisition, lack a structured methodology for deployment in construction environments. This paper proposes a domain-specific systems engineering framework to systematically transform existing GPSRs into operationally viable tools for construction project operations such as monitoring and inspection. Using a Modified V-Model with iterative prototyping loops, the framework integrates requirements engineering, modular system architecture design, and field-based validation. A case study based on a GPSR identifies functional gaps related to environmental variability, collaboration safety, and data interoperability. Implementation workflows demonstrate how GPSRs can be systematically integrated into construction projects. The results establish a reproducible engineering process that reduces development time and enables scalable, practical use of GPSRs on construction sites.

Keywords –

Construction Robotics; Digitalization; Mobile Robots; Monitoring; Requirements Engineering; Service Robots

1 Introduction

Experts believe that robotics has the potential to improve productivity in the construction industry [1]. However, its fragmented, project-based nature, dynamic environments, and reliance on conventional practices have slowed the adoption of robotics [1]. While other industries, such as manufacturing and agriculture, have successfully integrated robots, construction remains largely underserved. Existing solutions struggle with environmental variability, task versatility, safe human-robot collaboration, high cost of operation and maintenance, and integration with project workflows [1], [2]. General-purpose service robots (GPSRs) are general robotic platforms designed for monitoring and operational support in various environments such as factories and industrial facilities [3]. However, these robots are often not originally intended for the construction industry. Their adaptability, modularity, and robust sensing make them a promising foundation for new applications. This paper explores how GPSRs can be transformed to meet the unique demands of construction sites, overcoming current limitations while enhancing functionality, safety, and workflow integration. By leveraging existing capabilities in a new context, this paper aims to demonstrate a systematic pathway for robots to contribute to construction automation for the purpose of operation, monitoring, and maintenance.

1.1 Current Robotics Landscape in the Construction Industry

Most existing solutions are highly specialized for single tasks such as layout marking, welding, or inspection and are called Single Task Construction Robots (STCRs) [4]. While these systems demonstrate technical feasibility, they face persistent challenges:

- **Specialization and limited reuse:** Robots are often built for one task and certain site conditions, making it difficult to reuse them across different projects, phases, or dynamic environments [5]. This lack of generalization restricts long-term value and increases deployment costs.
- **High setup effort:** Many construction robots require extensive calibration, site preparation, or custom workflows, reducing the productivity gains that were intended [4].
- **Fragility in dynamic environments:** Frequent layout changes, unpredictable obstacles, dust, and weather can quickly degrade performance, cause

failures or require frequent human intervention [5].

- **High implementation cost:** High implementation and maintenance costs are often cited as one of the common challenges for construction practitioners to deploy robots [1], [6].
- **Cultural and legal constraints:** Despite technical viability and capability, implementation can also be hindered by site culture, workforce acceptance, and local regulations [1], [2].

In contrast, GPSRs have matured significantly in indoor industrial and commercial environments. The cost and price of general-purpose robots (e.g., service robots, industrial manipulators, humanoids) have continued to decline over the past years [7], largely due to growing scale and intense competition. They provide robust capabilities in:

- **Navigation and mapping:** Autonomous point-to-point and waypoint navigation with obstacle avoidance.
- **Perception and sensing:** Computer vision analysis, high-resolution photo/video capture, thermal imaging, and Bluetooth-enabled sensor data collection.
- **Data and communication:** Live streaming, long-term recording, and two-way communication via network connectivity for remote operations.

This contrast between the narrow, task-specific nature of current construction robots and the reusable capabilities of general-purpose robots creates an opportunity to explore how adaptable service robots can support construction project operations more effectively.

1.2 Problem Statement

To date, construction project operations remain heavily manual and inconsistent across sites. These operational tasks are critical for safety, progress tracking, and decision-making, yet they suffer from limited automation due to constantly changing environments and the lack of adaptable robotic platforms. At the same time, GPSRs have matured in navigation, sensing, and data collection, but are designed for controlled indoor settings such as offices, factories, and hospitals rather than construction sites. Despite advances in general-purpose robotics, there is no established methodology for adapting these systems to construction project operations. Construction sites are highly dynamic, unstructured, and often harsh, presenting challenges in:

- **Environmental variability:** Robots designed for controlled settings struggle with uneven terrain, dust, and constantly changing layouts.
- **Safety and human–robot collaboration**: Effective operation alongside personnel and machinery.
- **Task versatility**: Many operational tasks demand adaptability to irregular objects and variable conditions, yet existing robots are typically single-purpose.

These factors highlight the need for a reproducible engineering framework that systematically translates general-purpose robotic capabilities into safe, reliable, and operationally relevant tools for construction project environments

1.3 Objective

The objective of this study is to develop and (partially) validate a domain-specific systems engineering framework for rapidly transforming GPSRs to support construction project operations with clear requirements from the user. Specifically, the framework addresses inspection, monitoring, and workflow execution without requiring a full redesign.

2 Methods

To accelerate development and introduce more robotics companies to the construction industry, a domain-specific systems engineering framework was created to guide the transformation of GPSRs for on-site applications. Based on a case study, the methodology adapts established systems engineering principles, using a Modified V-Model for lifecycle structure and a structured requirements engineering process for concept development [8], [9].

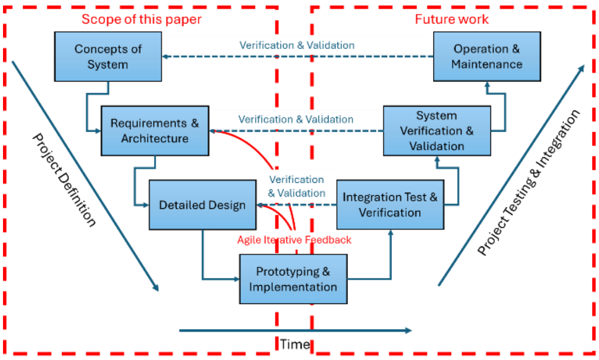

Figure 1. Modified agile V-Model in this research

2.1 Methodological Framework: The Modified V-Model

The V-Model was selected for its structured approach that links development phases with corresponding testing and validation activities. Since the original V-Model was developed for software development, our framework modifies this model by incorporating agile principles

(Figure 1) [8]. While the V-Model provides the overarching structure, small, informal iterative loops are introduced during prototyping to rapidly develop and test Minimum Viable Products (MVPs) [10]. This hybrid approach supports experimental validation of qualitative system features. This paper focuses on V-Model phases from "Concepts of System" through "Prototyping and Implementation," with later phases left for future work.

2.2 Requirements Engineering Process

A structured requirements engineering process is critical for translating multidisciplinary inputs into formal requirements and a coherent System Architecture. The systems engineering process (Figure 2), adapted from [8] and [9], begins with gathering Raw Requirements from domain-specific sources:

- **Key stakeholder interviews:** Structured interviews with key personnel such as site supervisors, engineers, robot operators, and environment safety contractors from the case study site in the target market are essential to understand their needs and pain points in daily construction project operations.
- **On-site observation via Gemba Walks:** Gemba (Japanese term for "real place") Walk is a lean management term referring to physically going to the real site where leaders can identify areas for improvement and cultivate a culture of continuous learning [11]. Direct observation of the construction environment through Gemba Walks at the case study construction site in the target market is essential to understand the dynamic conditions and conventional practices [12].
- **Market and state-of-the-art analysis:** Review of existing robotics solutions is helpful to identify common pitfalls and functional gaps.
- **Initial case study trial:** Baseline field test of GPSRs in the relevant environment is necessary to identify functional deficiencies and collect performance data.

Raw requirements are then converted into Formalized Requirements through (1) categorization, (2) reformulation using standardized syntax, and (3) assignment of reference codes. Requirements were grouped into Functional, Non-functional (i.e., performance), Domain (i.e., the construction sector), and Regulatory (i.e., especially relevant to the target market) categories [8].

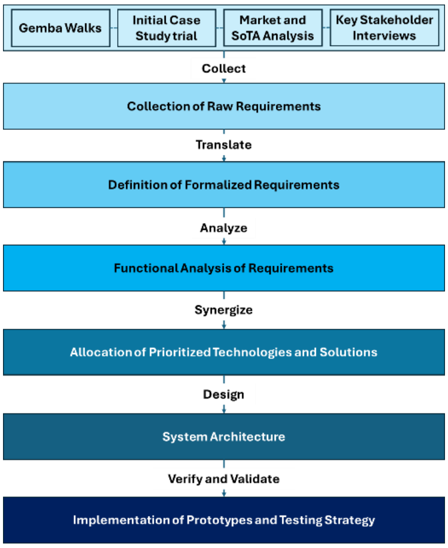

Figure 2. Requirements engineering methodological framework for rapidly transforming GPSRs to construction projects

2.3 System Architecture

Formalized requirements are organized to develop the system architecture, translating the "what" into the "how" [8]. The goal is to define a modular architecture that answers the research question: What system architecture enables modular transformation without full redesign? [9] Requirements are mapped to prioritized solutions—existing and new—to create a development roadmap. The resulting architecture blueprint forms the basis of the "Detailed Design" phase.

2.4 Detailed Design

The "Detailed Design" phase specifies the technical implementations derived from the system architecture. This includes selecting technologies and solutions and prioritizing them according to the requirements engineering outcomes [8]. The phase produces concrete hardware modifications and software integrations required to adapt a GPSR for construction tasks.

2.5 Prototyping and Testing Strategy

The framework then progresses to "Prototyping and Implementation". As outlined in Section 3.1, this phase uses an Agile methodology within the V-Model structure. Iterative prototyping is essential for construction environments where requirements evolve; prototypes validate individual functions quickly, enabling refinement until a stable system is achieved [5].

2.6 Integration Test and Verification

The next phase to be addressed in future work is the

"Integration Test, and Verification" phase. Once an MVP is produced, it undergoes live-environment integration testing. This stage employs the "Early Testing" loops [5] to confirm that the adapted system satisfies the functional requirements from Section 3.2 before progressing to full-scale deployment.

3 Results

As a highly developed tropical city state, Singapore has a robust economy and plays a pivotal role as a regional financial and innovation center in Southeast Asia, linking Eastern and Western markets. Its construction sector is one of the country's most important sectors, employing over 450,000 workers [13]. Like many countries, Singapore's construction sector faces persistent challenges such as stagnant productivity, construction waste, safety risks, labor shortages, and dependence on foreign workers [14]. Against this backdrop, government agencies have introduced a range of incentives to encourage both local and international firms to adopt innovative solutions in the built environment [12]. These conditions make Singapore an especially relevant and suitable setting for a case study, with the potential to scale the outcomes to other markets thereafter. This study introduces a commercialized GPSR platform from Japan to Singapore to explore how such platforms can be adapted to the construction industry in a completely different context (Figure 3).

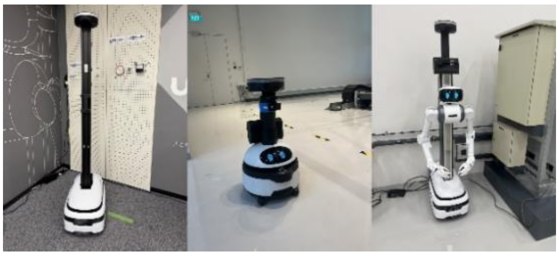

Figure 3. GPSRs in the case study (credit: ugo, Inc.)

A preliminary field trial was conducted over a 6-month period at an active large-scale manufacturing facility construction site to assess technical and environmental constraints and determine necessary operational requirements. The field trial included participants from the robot manufacturer, construction company, and various project contractors. The robot supported project operations by executing scheduled patrols, monitoring environmental parameters, and providing real-time surveillance. Quantitative and qualitative data were gathered regarding operational metrics, points of failure, and site characteristics. After the conclusion of the field trial, interviews with multiple project managers were conducted, which included feedback from staff members that interacted with the robots directly. The empirical data obtained from this case study, in conjunction with the requirements engineering framework detailed in Section 2.2, were utilized to form both raw and formalized requirements for the construction robot.

3.1 Requirements Engineering Output

Based on the requirements analysis of the key stakeholders, the raw and formalized requirements in Table 1 are split into four categories – Functional Requirements (FR), Non-Functional Requirements (NFR), Domain Requirements (DR), and Regulatory Requirements (RR), representing four key areas that the stakeholders wish to focus on the most.

Table 1. Outputs of requirements engineering process

Requirements No.	Requirements
FR01	**Raw:** Unsafe environment/hazard detection
	Formalized: Capability to detect unsafe environment conditions on construction sites such as holes, steps, and barricades
FR02	**Raw:** Movable live streaming camera
	Formalized: Capability to turn or move livestreaming camera up and down, left and right to monitor more angles (e.g., ceiling, floor)
FR03	**Raw:** Automatic route generation by easy parameter input
	Formalized: Enable user parameter input function to auto-generate robot patrolling route and automatically link routes in different rooms/areas
NFR01	**Raw:** Quick setup and maintenance
	Formalized: Improve and enable rapid system setup (i.e., plug-and-play setup), integration with site management software and smooth maintenance workflows
NFR02	**Raw:** Network connectivity and stability improvements
	Formalized: Improve weak/unstable Wi-Fi/5G signal connectivity issue at remote or underground location
DR01	**Raw:** Sensor protection
	Formalized: Improve design of GPSRs to keep sensors inside free from dust and water from construction sites
DR02	**Raw:** Large language model **(**LLM) functions customized for construction industry
	Formalized: Enable LLM voice

	function for construction specific context
RR01	**Raw:** Comply with Singapore regulations
	Formalized: Adhere to regulatory requirements in the following aspects – Built Environment and Productivity, Workplace and Risk Management, Environmental Health and Pollution, and Cybersecurity and Communication Compliance

3.2 System Architecture and Functional Design

State-of-the-art solutions were surveyed for each requirement to determine the essential technological components. These components were then stratified into their respective requirement categories for the construction sector (e.g., FR, NFR, DR, RR), yielding the system architecture depicted in Figure 4.

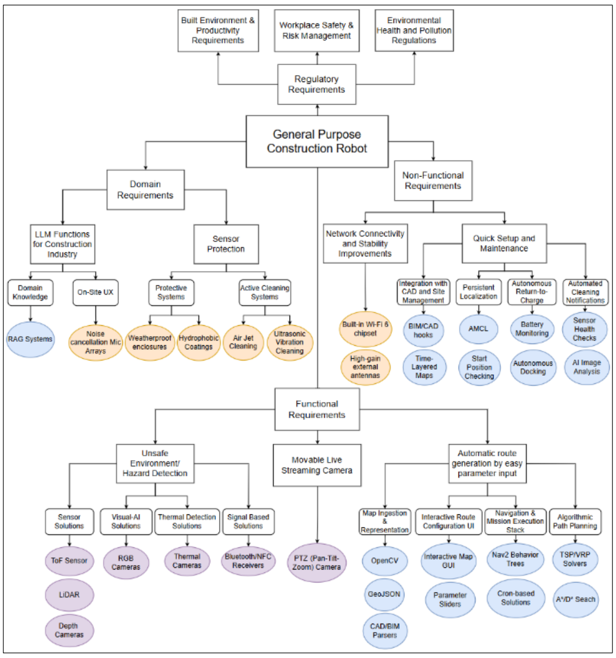

Figure 4. System Architecture of the adapted GPSR derived from requirements engineering

Functionally, it will support multi-modal hazard detection, movable live video streaming, and parameter-driven autonomous navigation. From a performance perspective, it enhances network connectivity and reliability while incorporating weatherproof protection for the sensors. Specifically for the construction sector, it integrates construction-focused LLM capabilities for domain knowledge and on-site interaction and enables quick setup and maintenance. Furthermore, it also complies with regulatory requirements in Singapore related to construction productivity, workplace safety, and environmental protection.

3.3 Development Planning

Based on the system architecture, a development plan was formulated following an evaluation of current systems and an analysis of requisite upgrades across the domains. Subsequent developments were defined based on solution feasibility and priorities, determined in collaboration with construction industry experts.

4 Implementation and Operational Workflow

Following the systems engineering and requirements definition process, the implementation phase aims to operationalize the proposed framework on real construction sites. Rather than focusing solely on technical upgrades, this stage emphasizes how a GPSR can be embedded into real-world construction workflows from preparation and deployment to charging, task execution, and data utilization.

This stage therefore functions as the robot's formal onboarding process. The implementation workflow bridges the gap between technical readiness and operational readiness, ensuring that the robot can function safely, autonomously, and efficiently within real project operations.

4.1 Site Preparation and Integration

Successful deployment begins with a structured preparation and integration process that ensures the robot's capabilities are safely and reliably embedded into site operations. Formalizing these steps makes deployment predictable, scalable, and repeatable across construction projects.

- **Site assessment:** A detailed survey identifies operational zones, access routes, hazard areas, and suitable dock locations. Terrain irregularities, material-strewn paths, temporary installations, and other construction hazards are mapped. Network coverage (Wi-Fi, 5G) is validated to ensure high-bandwidth connectivity across mission zones.
- **Infrastructure setup:** Setup includes installing charging docks, network repeaters, and safety markers along robot pathways. This step ensures stable power and safe dock placement. Physical boundaries are defined to prevent unintended entry into high-risk areas.
- **Software configuration:** Site layouts are imported into the mapping interface, followed by a calibration run to align digital maps with real

conditions. Digital no-go zones, speed-limited corridors, and temporary hazard boundaries are configured.

- **Connectivity integration:** Secure, stable data exchange is established between the robot's management portal and site systems, enabling real-time monitoring of position, mission status, battery level, and system's health.

4.2 Operational Workflow

Daily operation follows modular, repeatable workflows designed for efficiency, safety, and site awareness, balancing autonomy with human oversight.

- **Mission planning:** Operators define patrol, inspection, or monitoring tasks through a graphical user interface (GUI). Routes are generated based on the provided site maps. Typical tasks include safety compliance checks, environmental monitoring, hazard detection, meter readings, and routine visual inspections.
- **Autonomous execution:** The robot executes missions autonomously, navigating slightly uneven flooring, debris, temporary cables, and moving personnel. Onboard perception and hazard-detection algorithms support safe operation.
- **Data capture and reporting:** Images, sensor readings, and hazard detections are continuously recorded and uploaded to the management platform, where they are formatted into actionable reports based on site needs.
- **Human-robot coordination:** Personnel are briefed on robot operations, with clear escalation procedures for unexpected behavior. Supervisors can assign ad hoc tasks or trigger emergency stops without disrupting schedules.

4.3 Charging and Maintenance Procedures

Energy management and maintenance ensure reliable, safe autonomous performance and define the robot's Operational Design Domain (ODD) [15].

- **Autonomous return-to-charge:** After missions or at low battery, the robot automatically docks and begins charging, with status updates displayed in the operator's dashboard.
- **Maintenance scheduling:** Construction environments are particle-rich and harsh, which require proactive maintenance through scheduled tasks including: 1) Sensor integrity checks: Cleaning the LiDAR, cameras, and ultrasonics; running diagnostics, 2) Thermal management: Monitoring temperatures and clearing dust from cooling components, 3) Physical inspection: Checking wheels, actuators, seals, and enclosures for debris or damage, 4) Joint maintenance plan: Jointly defining a coordinated maintenance plan between the robot manufacturer and construction company and executing it by the construction company.

4.4 Workflow Adaptation for Construction Site

As construction environments evolve daily, robotic workflows must remain adaptive to maintain utility and relevance.

- **Periodic map uploads:** Operators upload site maps acquired from the site team, reflecting obstructions, and restricted zones, paralleling the site integration process.
- **Dynamic route regeneration:** The system recalculates routes when encountering new barriers, temporary structures, or shifting pathways, enabling safe navigation without manual reprogramming.
- **Collaborative operation:** Robotic tasks are synchronized with site operations - for example, performing patrols during off-hours, with supervisors reviewing inspection data at shift handover.
- **Data feedback loop:** Collected insights such as hazard detections, environmental metrics, and safety observations are fed back to the site team to facilitate regulatory reporting and proactive risk management.

4.5 Summary of Implementation Steps

The implementation plan follows a structured five-phase approach consistent with systems engineering, incorporating safety, maintenance, and integration practices required for construction sites (Table 2). Overall, implementation focuses on creating a structured yet adaptable operational environment where GPSRs can perform useful functions without a full redesign.

Table 2. Implementation plan derived from the requirements engineering process

Phase	Key Activities	Outputs
i. Preparation	Select pilot site; conduct survey; identify hazards; install dock, connectivity, and safety markers	Deployment-ready infrastructure and safety boundaries
ii. Integration	Import maps; configure no-go zones and tasks; perform calibration runs	Safe, validated operational test environment
iii. Field	Conduct autonomous	Operational

Operation	patrols; verify hazard detection; monitor logs, thermal health, and sensor integrity	data and performance logs
iv. Evaluation	Assess navigation reliability, data sync, detection accuracy, and worker–robot interaction	Pilot performance and safety compliance report
v. Optimization	Refine mission plans, update maps, adjust parameters, improve site workflows	A fully integrated, scalable operational framework

5 Discussion

The following sections highlight the methodology's novelty and effectiveness, the value of the engineering results, and the roadmap for future validation. In addition, the research limitations are outlined.

5.1 Novelty and Implications

The Modified V-Model successfully bridged the historical disconnect between robotic capabilities and construction realities in a rapid manner. By integrating "Gemba Walks", the framework captured dynamic site constraints, such as temporary cabling and dust accumulation, often absent from standard specifications. This observational data was directly formalized into the System Architecture and operational workflows, ensuring that the system was designed around real site operations (e.g., site induction & data handovers) rather than technical autonomy alone. Furthermore, the domain-specific requirements engineering process established a rigorous, traceable blueprint [8]. By linking every System Architecture component to specific "raw" requirements, the framework created a logical audit trail that prevented scope creep and ensured a demand-driven design. This rigor extended to defining a strict ODD [15], which explicitly mapped environmental boundaries such as surface flatness and lighting minimums to clarify the robot's role as a specialized tool for specific zones rather than a universal solution. Moreover, the systems engineering approach rapidly identified and specified all necessary components of the adapted GPSR, enabling early-stage cost-benefit analysis (CBA). By leveraging the established CBA framework for construction robots [16], key financial indicators of the adapted GPSR can be readily estimated prior to on-site deployment, which not only further validates the feasibility of the adapted robot but also strengthens client confidence.

5.2 Limitations

While the framework establishes a robust structural foundation, several requirement categories were excluded from this initial iteration. These limitations fall into three distinct aspects. First, addressable scope limitations such as advanced AI integration (e.g., LLMs) and local 5G infrastructure analysis were deferred to prioritize immediate feasibility but remain part of the future development roadmap. Second, inherent hardware constraints impose fixed operational limits. Specifically, the GPSR's wheel configuration restricts movement on rough terrain, a physical limitation that cannot be resolved through framework adaptation. Furthermore, as the study focuses on framework development, long-term feedback and quantitative metrics have not yet been gathered for verification and validation.

6 Conclusion

This paper presents a domain-specific systems engineering framework for rapidly transforming GPSRs into operational tools for construction project environments. By integrating a Modified V-Model with structured requirements engineering, the proposed framework offers a reproducible methodology that bridges the gap between controlled-indoor robotic platforms and the complex, dynamic conditions of construction sites, laying out the foundation for the next-phase development. The case study demonstrates that, while current GPSRs possess strong baseline capabilities in navigation, sensing, and data acquisition, they require systematic adaptation to address construction-specific challenges such as environmental variability, human–robot collaboration, and workflow integration. With the completion of the remaining work, the study is expected to fully validate the effectiveness and practicality of the proposed methodological framework.

The study mainly benefits construction project teams and robotics providers who want to deploy GPSRs for real site operations without the need for a full robot redesign, further lowering development cost, and accelerating development speed. More broadly, it provides a valuable reference for those who wish to rapidly adapt general-purpose technologies to new application scenarios and industries.

As indicated in Figure 1, future work will advance the project from the "Detailed Design" phase into the "Prototyping and Implementation" phase of the V-Model, eventually verifying and validating the system design, requirements, and project concept. The specific roadmap includes:

- **Prototyping and implementation:** Executing iterative prototyping loops to integrate sensing payloads and software modules.

- **Site testing:** Conducting field trials to validate performance under real conditions and collect quantitative data on localization and docking reliability.
- **Regulatory compliance and expansion:** Addressing deferred scope items, achieving compliance with Singapore's (and potentially other target markets') safety regulations, and integrating capabilities such as LLMs and 5G connectivity.
- **Iterative refinement:** Using site-testing results to drive feedback loops that may return the process to requirements engineering, system architecture, or detailed design for further optimization.

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