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Article

A Scalable Vertical ASRS Architecture for SMEs with AI-Based Maintenance Support and Retrieval Optimization

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Abstract: —Vertical automated storage and retrieval systems (ASRSs) are a promising technology to improve space utilization and order-picking consistency, but the adoption of ASRSs by small and medium enterprises (SMEs) is limited by acquisition cost, integration effort, unscheduled stoppages, and inefficient tray sequencing. In this paper, we propose an integrated and repeatable simulation framework arranged by five interconnected components: system design, cost and scalability, safety credibility, AI-supported condition monitoring, and priority-aware retrieval scheduling. A parametric full system CAPEX/TCO model and a controller-stack scale study address the first objective; rack and trolley terms are still replaceable by supplier-dependent ones. The second objective is formulated as a maintenance alert categorization rather than a remaining useful life estimate. We use a Random Forest with 180 trees and a stratified five-fold cross-validation on 4,500 physically bounded synthetic samples. The third objective uses a distance-age-priority score, selected during validation, and compares it to FIFO and nearest-tray strategies using 2,000 paired test batches. At five identical units, the hybrid fail-safe stack saves 12.0% of controller CAPEX compared to PLC control. The classifier reaches an accuracy of 91.7%, a macro-F1 of 0.917 and Fault recall of 92.1%. The scheduler reduces journey distance by 59.7% and priority-weighted completion time by 8.9% against FIFO. These results offer preliminary design evidence, but no field validation, full system cost proof, or functional safety certification.
Keywords: - automated storage and retrieval system, vertical lift module, SME automation, condition monitoring, retrieval scheduling, total cost of ownership.

1. INTRODUCTION

Goods-to-person systems, such as vertical lift modules (VLMs), utilize vertical space, save operator walking and allow for more uniform order selection. But their actual performance depends on service-time distributions, storage assignment, tray configuration, workload intensity, mechanical design and quality of integration [2], [5]-[13],For SMEs, these technical challenges are compounded by tight capital budgets, low automation skills, reliance on external integrators, and the economic impact of extended downtime [1], [4], [7].

Useful models for ASRS design, VLM throughput, economic evaluation, order allocation and controller dependability are provided by existing research, but often these strands are treated in isolation. PLC work is on deterministic sequencing, verification and fault handling [3], [19]-[22], [33], while warehouse optimization work is on configuration, storage assignment, walking distance or request allocation [8], [11], [30]-[35]. This separation makes it hard for a SME to know whether a lower-cost controller, maintenance-support layer and retrieval policy fit together under a similar plant and safety boundary.

Hence the current work is a limited simulation study and not a field validated product. Mechanical costs are parameterized with respect to the supplier, synthetic condition data is used only to test the software pipeline, and benefits of retrieval are provided under explicit motion and service-time assumptions. The project has three objectives: O1: design and evaluation of a low-cost, modular and scalable vertical ASRS for SMEs; O2: implementation of an AI-assisted maintenance-support module based on operational indicators; O3: design of an intelligent retrieval scheduler to improve efficiency and overall system performance.

Main contributions are: (i) a modularized full-system CAPEX/TCO formulation including scale analysis of the controller stack; (ii) a structured literature synthesis connecting ASRS economics, industrial control, condition monitoring, and retrieval optimization; (iii) a reproducible condition-classification baseline with released parameters and cross-validation; (iv) a priority-aware scheduling heuristic with validation-based weight selection; and (v) an explicit boundary of evidence between preliminary simulation results and certification or field performance-claims.

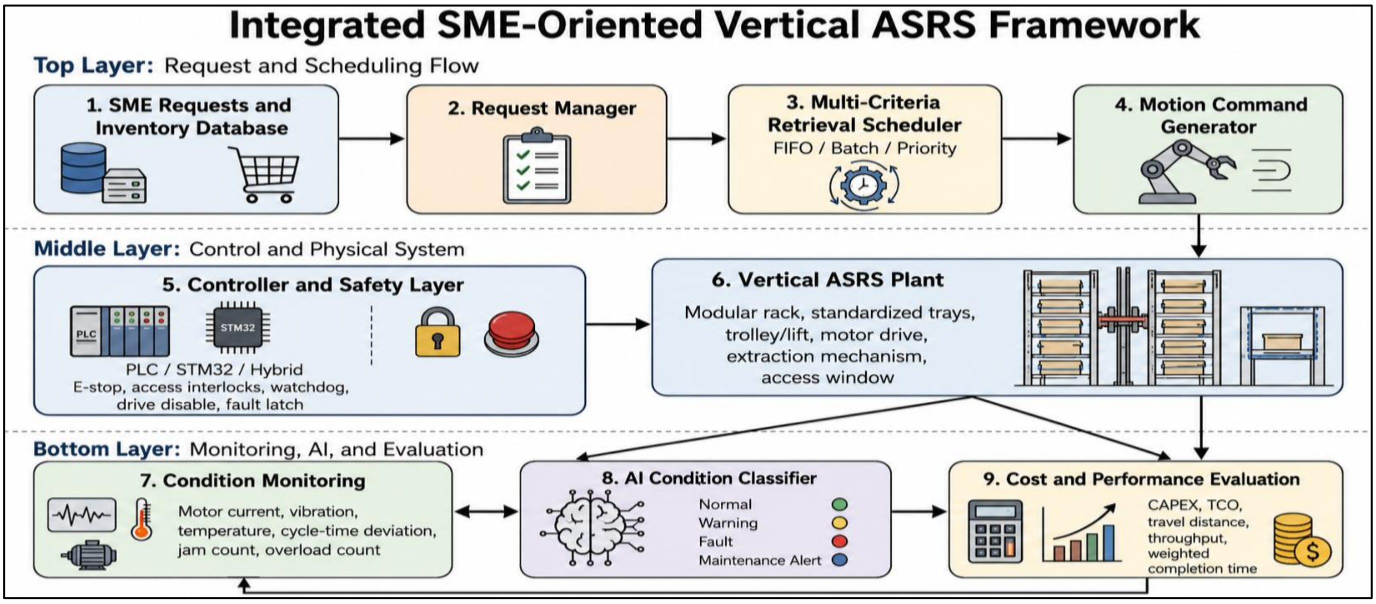

Fig. 1. Integrated SME-oriented vertical ASRS architecture and their evidences boundary

2. LITERATURE SURVEY AND RESEARCH GAP

A. Modelling ASRS and VLM performance

ASRS surveys have shown that system performance [2], [35] is affected by storage policy, travel-time modeling, configuration and control method. Then, throughput and service-time models for single-tray, dual-tray and buffer integrated setups were developed for carousel and VLM investigations [6, 10, 12, 17, 18, 21, 24, 28, 36, 37]. The effectiveness of VLMs is sensitive to the use of trays, the service by operators, the setting of the facility, and the quality of implementation [5], [7], [9], [16], [25], [26], [38] based on case-based and thesis research. These results support the current practice of a specified mechanical envelope and workload contract rather than a universal single throughput value.

B. Economic design, use of vertical space and SME adoption

The economic evaluations show that the use of VLMs must be evaluated based on factors other than the purchase price, since layout, space utilization, operator movement and lifecycle service requirements affect the realized benefit [4], [7], [13], [15], [26], [29]. The work on modular redesign and vertical-space utilization suggests that component rationalization and local fabrication can enable affordability, but site-specific dimensions and quotes are still required [15], [29]. The research also supports the importance of energy and lifecycle perspectives from a sustainability point of view. However, this paper considers only travel distance as a proxy for energy, since drive-level power measurements are not available [1].

C. Controller architectures, reliability and safety practices

Research in the area of PLC and embedded-control supports deterministic execution, verification, reconfiguration, failover and timing [3], [19]–[22], [33]. These results motivate a controller comparison that does not consider a low-cost MCU as a direct drop-in replacement of an industrial PLC. Instead, the hybrid stack described here separates the productivity logic from the hardwired emergency-stop, access-interlock, watchdog, and drive-disable operations. The unpublished controller review [14] is kept only as a contextual support, but not as a primary evidence.

D. Storage allocation, decision support and retrieval scheduling

Research on order allocation, item assignment, layout optimization and data-driven decision support has demonstrated that retrieval efficiency is not only determined by the immediate trip distance [8], [11], [30]-[34]. FIFO respects the order of arrival, but might involve too much travel. Nearest-tray minimizes travel for the current requests, but might delay old or priority requests. Further human-factors and order-picking evaluations indicate that workload design and operator interaction influence system-level productivity [25], [27], [34], [35]. This motivates a multi-criteria policy that balances distance, waiting age and request priority.

E. Synthesis of literature and clear research gap

The literature presents four mature, yet loosely coupled, themes: VLM performance modeling, ASRS economics, dependability of industrial controllers, and retrieval optimization. What is not sufficiently addressed is a compact SME-oriented approach to analyze different themes under the same plant boundary and to make claim restrictions clear. The present work addresses this gap at simulation level through the integration of controller scale economics, maintenance alert categorization, safety oriented architecture and priority aware retrieval scheduling. It does not claim a new mechanical machine, verified fault prognosis, measured energy saving or certified functional safety.

Theme	Primary focus	Representative references	Role in this study
ASRS/VLM modeling	Travel, throughput, configuration, service time	[2], [6], [10], [12], [17], [18], [21], [24], [28], [36], [37]	Supports motion and workload assumptions
Economics and SME adoption	Lifecycle cost, ROI, space use, deployability	[4], [7], [9], [13], [15], [26], [29]	Supports parametric CAPEX/TCO framing
Controller dependability	PLC verification, timing, reconfiguration, failover	[3], [19]-[22], [33]	Supports PLC/MCU/Hybrid boundary
Retrieval optimization	Allocation, storage assignment, layout, decision support	[8], [11], [30]-[35]	Supports FIFO/nearest/proposed comparison
Human and operational context	Operator movement, picking process, implementation cases	[5], [16], [25], [27], [38]	Supports service-time and SME assumptions

TABLE I. Literature synthesis and it's relationship with the proposed framework.

3. PROPOSED SYSTEM ARCHITECTURE AND OBJECTIVE MAPPING

Figure 1 shows the framework in three layers. The upper layer handles requests, inventory information, batch formation, and multi-criteria scheduling. The middle layer consists of the fixed vertical ASRS plant and the replaceable controller stack. The lowest level receives status indicators, classifies the health of the machine and considers economic and operational outputs. This multi-layered segregation enables a SME to implement the base machine and then enable maintenance analytics or advanced scheduling without having to re-engineer the physical plant.

Objective	Implemented evidence	Primary metrics	Claim boundary
O1: Cost/scalability	Parametric rack, trolley, drive and integration terms; PLC/MCU/Hybrid controller scale model	CAPEX, TCO, scale N, reduction	Numerical result is controller-stack only
O2: Maintenance support	Random Forest condition classifier with five-fold cross-validation	Accuracy, macro-F1, Fault recall	No RUL or time-to-failure claim
O3: Retrieval optimization	Validated distance-age-priority scheduler	Distance, throughput, weighted completion	Travel is an energy proxy only

TABLE II. Objective-to-evidence mapping.

4. SYSTEM MODEL AND METHODOLOGY

A. Reference architecture and operating boundary

The reference plant is a vertical ASRS with single access window, consisting of a modular rack, standardized trays, a trolley or lift, drive and transmission elements, position and safety sensors and an operator presentation point. Architecture A is based on a PLC-centric stack; Architecture B is based on an STM32-class controller with industrialized I/O; Architecture C combines embedded productivity logic with an independent hardwired fail-safe layer. All alternatives have the same mechanical boundary, I/O contract, and retrieval workload.

B. Formulation of cost and scalability

The model distinguishes non-recurring engineering from the mechanical, automation, and commissioning cost per unit for N identical units. Let C_NRE denote reusable engineering, C_mech the rack, trays, trolley/lift and drive cost per unit, C_auto the controller, sensing, safety, panel and HMI cost per unit, and C_u the per-unit integration cost. Annual ownership terms includes the maintenance, energy, and downtime. For a five-year horizon Y = 5:

$$C_{CAPEX(N)} = C_{NRE} + N(C_{mech} + C_{auto} + C_{u}) \quad (1)$$

$$C\_TCO(N) = C\_CAPEX(N) + Y\left[C_{maint(N)} + C_{energy(N)} + C_{down(N)}\right] \quad (2)$$

$$\text{Reduction}(\%) = 100 \times \frac{(C_{base} - C_{prop})}{C_{base}} \quad (3)$$

No rack dimensions, materials, fabrication quotes and installation rates were presented. The numerical scale study thus quantifies only the approved controller-stack component, the mechanical symbols remain replaceable by site quotations. The reported 12.0% reduction is thus a controller-stack CAPEX result, not a full-ASRS savings.

C. AI for condition monitoring

The condition vector includes vibration RMS, motor current, motor temperature, cycle-time deviation, jam count and overload count. Samples are labelled as Normal , Warning or Fault . Continuous features are distributed as overlapping Gaussians and event counts are non-negative rounded values. These distributions are assumptions from engineering simulations to test reproducibility, not validated alarm thresholds.

$$x = \left[v_{rms}, I_m, T_m, \Delta t_{cycle}, n_{jam}, n_{overload}\right] \quad (4)$$

The model a Random Forest with 180 trees, maximum depth 10, minimum leaf size 3, balanced class weights and seed 20260725, and it is evaluated with stratified five-fold cross-validation. The overall confusion matrix is built from the out-of-fold predictions. The model is used for classification of maintenance alerts and not for the estimation of remaining useful life, failure probability or time-to-failure.

D. Scheduling of priority-aware retrieval

Each batch has eight tray requests, each with a tray height, a waiting age and a priority. FIFO serves arrival order, while nearest-tray reduces the overall immediate movement. The proposed policy normalized the distance d_i*, age a_i*, and priority p_i* and selects the minimum validated score. Weights are chosen based on the 500 independent validation batches by grid search under w_d + w_a + w_p = 1, minimizing a specified objective combining normalized travel distance and priority-weighted completion time.

$$S_i = 0.70 d_i * - 0.10 a_i * - 0.20 p_i * \quad (5)$$

$$T_r = T_{move} + T_{extract} + T_{settle} + T_{service} + T_{queue} \quad (6)$$

Movement follows a triangular or trapezoidal profile over a 6 m height with the maximum speed of 1.0 m/s and acceleration 0.8 m/s². Extraction, settling, and operator service are 6 s, 2 s, and 20 s. Throughput equals completed requests divided by total simulated batch time. Travel distance is reported only as an energy proxy.

5. EXPERIMENTAL SETUP, REPRODUCIBILITY, AND SAFETY VERIFICATION

A. Reproducible workflow and simulation controls

The condition-monitoring experiment uses 4,500 samples, 1,500 per class. The retrieval evaluation uses 2,000 paired test batches generated from identical random requests for all policies, thereby controlling workload variation. A separate 500-batch set is used only for scheduler-weight selection. Random seeds, distributions, model hyperparameters, motion values, request count, and trial count are disclosed below to permit independent regeneration of the reported results.

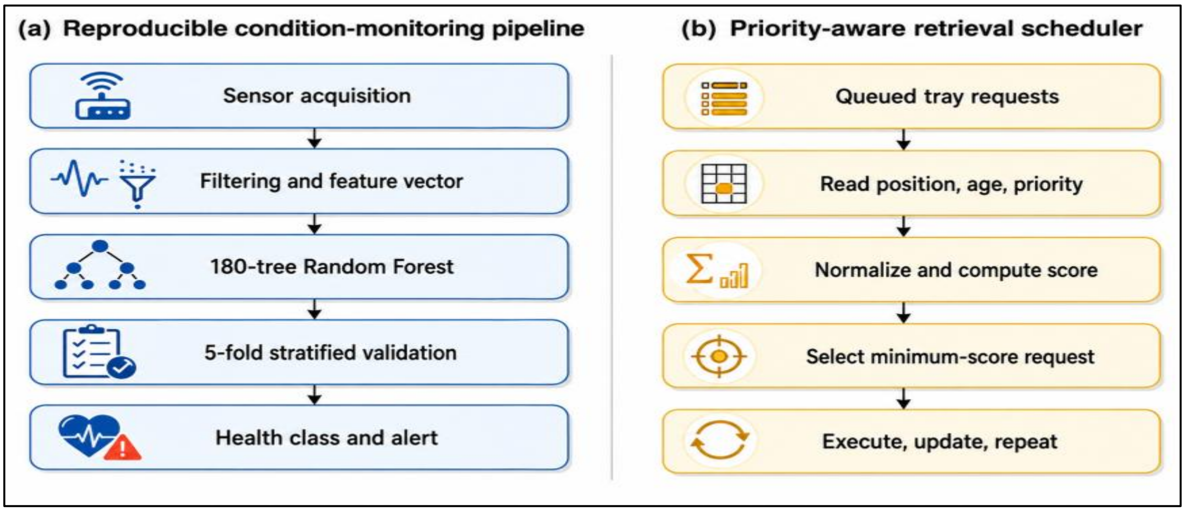

Fig. 2. Reproducible condition-monitoring and retrieval-scheduling workflows.

Parameter	Normal	Warning	Fault / simulation
Vibration RMS (mm/s)	2.0±0.65	3.3±0.85	4.8±1.05
Current (A); temperature (°C)	4.2±0.75; 45±6	5.2±0.95; 55±7	6.5±1.15; 66±8
Cycle deviation (%); jam/overload	1±4; 0.4/0.2	7±6; 1.3/0.8	14±8; 2.5/1.6
Classifier controls	1,500 samples/class	5-fold stratified CV	RF: 180 trees; seed 20260725
Retrieval controls	6 m; 1.0 m/s; 0.8 m/s²	8 requests/batch	500 validation + 2,000 paired tests

TABLE III. Disclosed synthetic-data and simulation parameters.

B. Retrieval scheduler procedure

Algorithm 1 operates on pending request set Q and current trolley position z. At each iteration it computes absolute travel distance, min-max normalizes distance, waiting age, and priority over the current queue, evaluates S_i, selects the minimum-score request, applies earlier arrival as a deterministic tie-breaker, appends the request to the service sequence, updates z and the waiting ages of unserved requests, and repeats until Q is empty. Repeated selection has $O(n^2)$ time for n requests, which is negligible for the eight-request batches considered here.

Step	Operation
Input	Request set Q, current position z, weights (0.70, 0.10, 0.20)
1	While Q is not empty, compute distance, age, and priority for every request.
2	Normalize each criterion over the current queue.
3	Evaluate S_i and select the minimum-score request; break ties by earlier arrival.
4	Append the request to the schedule, update z and waiting ages, and remove it from Q.
Output	Priority-aware retrieval sequence.

Algorithm 1. Priority-aware multi-criteria retrieval scheduling.

C. Safety verification plan

The simulation does not certify functional safety, but the architecture defines a falsifiable hardware-in-the-loop verification plan. A safe state means that motion commands are inhibited, the drive-enable path is removed, braking is engaged where applicable, and restart is prevented until the initiating condition is cleared and an operator reset is accepted.

Hazard	Detection	Safe action	Verification intent
Access door opened during motion	Hardwired door interlock	Remove drive enable; inhibit motion; latch	Open-door injection during commanded travel
Vertical over-travel	Independent limit switch	Controlled stop, brake, and fault latch	Activate upper/lower limit in test mode
Controller execution freeze	Watchdog timeout	De-energize drive-enable path	Suspend control task and verify timeout response
Tray jam or overload	Current/overload signal and timeout	Stop motion and hold tray state	Inject overload and delayed-position feedback
Power interruption/brownout	Undervoltage supervision	Boot to safe-off; no automatic restart	Power-cycle at multiple operating states

TABLE IV. Hazard-to-safe-action and verification mapping.

D. Statistical reporting

Classification results use out-of-fold predictions across five stratified folds. Scheduling policies are evaluated on identical request batches and 95% confidence intervals are calculated from paired trial differences. This paired design isolates policy effects more effectively than independently generated workloads. Error bars in Fig. 3(c) represent 95% confidence intervals of the mean.

6. RESULTS AND DISCUSSION

A. Cost and Scalability of Controller Stack

CAPEX of PLC, MCU and hybrid controller at N = 5 is INR 12,37,615, INR 10,57,480 and INR 10,88,480 respectively. The hybrid controller stack is thus 12.0 % below PLC while maintaining an independent hardwired safety layer. Reuse of MCU and hybrid engineering is amortized across same devices at bigger size. Embedded alternatives have higher non-recurring engineering. The PLC is competitive in small scale . The above values exclude the manufacture of unquoted rack and trolley.

B. Condition monitoring results

The Random Forest model achieves 91.7% accuracy with a standard variation of 0.8% from fold to fold, a macro-F1 of 0.917, and a Fault recall of 92.1%. Most errors occur between adjacent Warning and Fault states, and no direct Normal-Fault confusion is detected. The result demonstrates the behavior and reproducibility of the pipeline, not predictive validity on an industrial ASRS, as labels are obtained from controlled synthetic distributions.

C. Scheduling of retrieval results

Across 2,000 paired test batches, mean distances are 17.01, 5.31 and 6.86 m for FIFO, nearest-tray and suggested scheduling. Average throughput is 115.07, 121.43 and 120.49 requests/h while priority-weighted completion time is 141.08, 133.71 and 128.47 s respectively. The proposed technique reduces travel by 59.7% and weighted completion by 8.9% compared to the FIFO. It incurs a distance penalty compared to nearest-tray, but improves weighted completion by 3.9%. This demonstrates the desired fairness-efficiency trade-off.

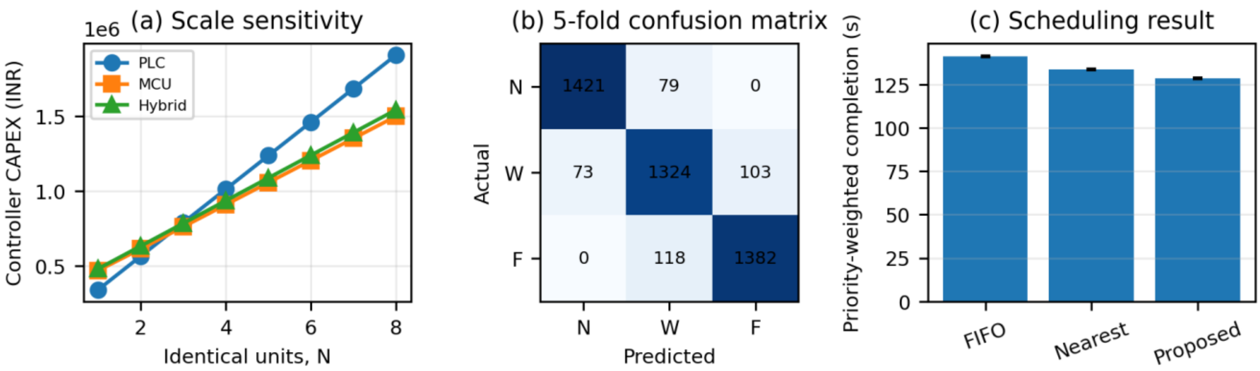

Fig. 3. Results: (a) controller-stack CAPEX sensitivity, (b) aggregate out-of-fold confusion matrix, and (c) mean priority-weighted completion time with 95% confidence intervals.

Module/method	Metric	Result	Interpretation
Cost, N=5	PLC / MCU / Hybrid CAPEX	1,237,615 / 1,057,480 / 1,088,480 INR	Controller stack only
Condition model	Accuracy / macro-F1 / Fault recall	91.7%±0.8% / 0.917 / 92.1%	Synthetic, five-fold CV
FIFO	Distance / throughput / weighted time	17.01 m / 115.07 h^{-1} / 141.08 s	Arrival-order baseline
Nearest	Distance / throughput / weighted time	5.31 m / 121.43 h^{-1} / 133.71 s	Shortest immediate route
Proposed	Distance / throughput / weighted time	6.86 m / 120.49 h^{-1} / 128.47 s	Priority-aware compromise
Safety	Hazard response	detect → stop → safe → latch → reset	Architecture-level plan only

TABLE V. Result summary and their claim boundaries.

D. Discussion

The three objectives affect different aspects of ownership burden. Modular design and engineering reuse lower the upfront cost, condition monitoring enables earlier intervention and a more systematic failure response, and retrieval scheduling reduces unnecessary movement and priority delay. None of the modules make ASRS costlier. The integrated framework instead disaggregates affordability into capital, reliability, and operational-efficiency mechanisms. The hybrid approach is attractive where a SME wants embedded scale economics, but must have a standalone safety border. Where service familiarity and avoiding down-time are paramount, PLC still remains the preferred choice.

The scheduling results also show that shortest-route performance is not a good system objective. The nearest-tray minimizes immediate movement; the proposed policy improves upon priority-weighted completion by explicitly accounting for waiting age and importance. The strong condition-classification score should not be interpreted as predictive maintenance performance either, since the dataset does not represent temporal degradation or true failure histories.

7. LIMITATIONS, THREATS TO VALIDITY AND FUTURE WORK

The first limitation is economic, we don't have the whole mechanical BOM, dimensions, material grades, local manufacturing rates and supplier's quotations. So the quantified result of 12.0% is valid for controller-stack CAPEX only. Second, the condition-monitoring data is synthetic and does not demonstrate remaining useful life, probability of future failure, diagnostic coverage or field false alarm rates. Third, travel distance is used as a surrogate for energy. Real savings require quantifiable drive power, payload, efficiency and regenerative behavior. Fourth, workload is eight-request batches, one access window and set operator service time, while actual SME demand is nonstationary and human service is variable. Finally, the safety plan is standards aware, but not certified, and requires hardware in the loop fault injection and an independent compliance review.

To mitigate threats to internal validity, we employ fixed random seeds, independent validation and test batches, out-of-fold prediction, and paired scheduler comparisons. Still the external validity is limited because the mechanical dimensions, workload patterns, maintenance procedures and local expenses vary from site to site. Explicit metric definitions and claim boundaries maintain construct validity. Future work is needed to link the simulation metrics to observed machine behavior.

8. CONCLUSION AND FUTURE WORK

This work proposes a complete and reproducible vertical ASRS framework for SMEs including literature survey, architectural justification, experimental setup, algorithm description, safety verification plan, statistics reporting and threats-to-validity discussion which were missing from prior works. The stated economic benefit is a 12.0% controller-stack CAPEX reduction for the hybrid design at five units over PLC control. Full-system savings require an actual rack, trolley, drive, fabrication and installation BOM. The Random Forest provides a clear baseline for classification of maintenance-alerts but not for a predictive-maintenance claim in the field. The distance-age-priority scheduler, validated, beats FIFO and publicly accounts for its tradeoff over nearest-tray routing.

Future work should include a replacement of parametric mechanical terms with supplier quotations and build a laboratory scale prototype. Synchronous collection of current-vibration-temperature histories, drive energy measurement, temporal fault-prognosis model evaluation, fault-injection and hardware-in-the-loop testing, and validation of scheduling under nonstationary demand, multiple operators and larger request batches. Further studies on deployment should present maintainability metrics like mean time to repair, diagnostic coverage, availability, and observed downtime cost.

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