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Research Paper Title :Hybrid Quantum-AI Scheduling and Adaptive Robotic Skill Transfer for Photonic-Neuromorphic Industrial Autonomous Systems

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Abstract:

Industrial autonomous systems increasingly require simultaneous optimization of machine schedules, robotic skills, perception latency, energy use and safety under dynamic production conditions. Existing research treats several of these problems separately: quantum-assisted scheduling targets combinatorial search, language-guided manipulation addresses skill selection, neuromorphic perception reduces event-to-action latency, and photonic hardware offers high-throughput low-energy signal processing. This paper integrates these strands into a unified model-based architecture termed the Hybrid Quantum–Photonic Adaptive Skill Transfer (HQ-PAST) framework. The framework couples a hybrid quantum-AI scheduling layer with a cross-platform skill-embedding layer, photonic-neuromorphic sensory processing, a digital-twin constraint monitor and closed-loop robotic execution. A mathematical formulation combines multi-objective scheduling, graph-based skill transfer, state-space dynamics, probabilistic execution risk and energy-aware optimization. An illustrative 0–10 numerical model demonstrates how scheduling efficiency, skill-transfer fidelity, neuromorphic responsiveness, photonic energy efficiency, safety compliance and digital-twin fidelity can be aggregated into a risk-adjusted autonomy score without claiming empirical validation. The analytical results indicate that the architecture is most valuable where task allocation and embodied skill adaptation must be recomputed under tight latency and reliability constraints. The paper contributes an interdisciplinary systems framework, implementation logic, validation pathway and an invention-oriented disclosure comprising a technical problem, novel architecture, system and method claim concepts, and dependent claim concepts. The proposed contribution is intended for subsequent empirical validation on industrial robotic cells and for formal prior-art and patentability assessment before any filing decision.

Keywords

hybrid quantum-classical reinforcement learning; quantum scheduling; adaptive robotic skill transfer; photonic neuromorphic computing; embodied manipulation; industrial autonomy; digital twins; event-driven perception; skill embeddings; flexible manufacturing systems; low-latency industrial IoT; autonomous scheduling; multi-objective optimization; predictive maintenance; cyber-physical production systems

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1. Introduction

Industrial automation is shifting from preprogrammed, cell-specific control toward systems that must interpret changing goals, reschedule constrained resources, transfer learned manipulation skills and react to sensory events with minimal delay. The resulting control problem is not simply robotic motion planning. It is a joint decision problem linking production scheduling, embodied skill selection, machine availability, energy budgets, communication latency, tool state, safety rules and uncertainty about process outcomes. Language-guided hybrid skill scheduling illustrates the move toward dynamically composed embodied skills, while hybrid quantum-classical reinforcement learning and quantum-assisted manufacturing scheduling indicate that combinatorial scheduling can be reformulated for emerging optimization resources (Si et al. 2026; Gu et al. 2026; Bożejko et al. 2026).

At the physical control boundary, neuromorphic sensing and photonic computing offer a complementary route to low-latency autonomy. Neuromorphic visuotactile perception can provide sparse event-driven signals for manipulation, and self-adaptive photonic synapses point toward hardware that can modify responses without repeatedly invoking a power-intensive cloud stack (Qiao et al. 2026; Chen et al. 2026). Photonic memory and signal processing further suggest that optical devices may support high-bandwidth temporal processing for neuromorphic workloads (Saffer et al. 2026). These developments motivate a system architecture in which scheduling intelligence and embodied perception are co-designed rather than connected as independent modules.

Industrial deployment also requires robustness beyond nominal task completion. Low-latency instruction segmentation over hybrid industrial links establishes communication as a scheduling variable, while digital-twin and predictive-maintenance research demonstrates the importance of machine-state estimation, remaining-useful-life uncertainty and maintenance constraints in autonomous decision making (Liu et al. 2025; Mehdipour et al. 2026; Omoloja et al. 2026). A practical autonomous system therefore requires a constraint-aware loop in which perception, scheduling, skill transfer and maintenance state continuously inform one another.

The central research gap is the absence, within the supplied literature corpus, of a single integrated model that explicitly couples hybrid quantum-AI scheduling with transferable robotic skill representations and photonic-neuromorphic execution while retaining a digital-twin constraint layer. This paper addresses that gap through the HQ-PAST framework. It is a model-based conceptual and mathematical study; it does not claim experimental proof and uses illustrative numerical values solely to demonstrate the logic of evaluation.

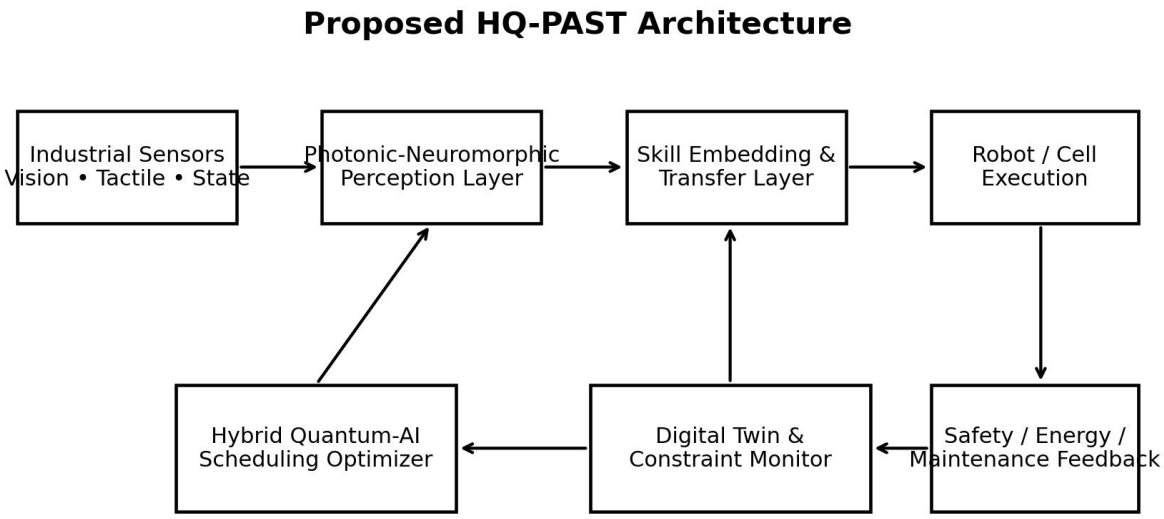

Figure 1. Proposed HQ-PAST architecture integrating quantum-AI scheduling, photonic-neuromorphic perception, skill transfer, robotic execution and digital-twin feedback.

Research Problem

Industrial autonomous systems face a coupled optimization problem: production schedules become invalid when machine state, communication latency, robot embodiment or sensory uncertainty changes, while robot skills learned on one platform often require costly retraining before reuse elsewhere. Conventional modular architectures separate scheduling from perception and skill adaptation, causing delayed rescheduling, duplicated learning and poor propagation of safety or

maintenance constraints. The technical problem is to provide a low-latency architecture that jointly selects production actions, transfers robot skills across heterogeneous embodiments, processes event-driven sensory updates, and continuously enforces resource, safety, energy and machine-health constraints.

1.1 Research Questions

- RQ1. How can hybrid quantum-AI optimization be combined with real-time industrial scheduling without disconnecting schedule quality from robotic execution constraints?
- RQ2. How can transferable robotic skills be represented so that a learned manipulation primitive can be adapted across heterogeneous robot platforms and production cells?
- RQ3. What role can photonic-neuromorphic sensing and processing play in reducing perception-to-action latency and energy consumption within autonomous manufacturing?
- RQ4. How should digital-twin, safety, communication and maintenance constraints be incorporated into a joint scheduling-and-skill-transfer objective?
- RQ5. Which validation metrics are necessary to distinguish useful system-level integration from isolated improvements in scheduling, perception or control?

1.2 Research Objectives

- Develop an integrated architecture linking hybrid quantum-AI scheduling, photonic-neuromorphic perception and robotic skill transfer.
- Formulate a multi-objective mathematical framework covering makespan, energy, transfer error, latency, risk and maintenance constraints.
- Construct an illustrative normalized numerical model for system-level comparison without implying empirical validation.
- Define implementation variables, interfaces, validation metrics and ablation scenarios for future industrial testing.
- Produce an invention-oriented technical disclosure and claim-concept structure grounded in the supplied literature corpus.

2. Literature Review

Hybrid scheduling and quantum-AI optimization

Si et al. (2026) position skill scheduling as a language-guided embodied manipulation problem in which high-level task intent must be converted into feasible combinations of skills. Gu et al. (2026) provide a direct bridge to hybrid quantum-classical reinforcement learning for scheduling systems, while Bożejko et al. (2026) place autonomous AI and quantum computing in flexible-manufacturing scheduling. Together, these works establish a credible conceptual basis for separating a difficult combinatorial decision layer from the physical execution layer. The limitation is that schedule quality alone does not guarantee transferability of skills across different robots or low-latency adaptation to contact events.

Robotic skill transfer and neuromorphic perception

Qiao et al. (2026) demonstrate the importance of neuromorphic visuotactile perception for manipulation, which is especially relevant when slip or contact transitions must alter a scheduled action before failure. Chen et al. (2026) extend the hardware perspective through a self-adaptive all-photonic synapse for autonomous neuromorphic robots. These contributions support a local, event-driven control plane. However, they do not by themselves solve the higher-level problem of deciding which task should be assigned to which robot, when, and with what skill adaptation.

Industrial communication and autonomous edge

Liu et al. (2025) treat instruction segmentation and scheduling over hybrid Industrial IoT links, indicating that communication delay and link availability are structural variables in autonomy rather than mere networking details. Vermesan et al. (2026) describe convergence between AI and autonomous edge systems in the context of AI-defined vehicles; the architectural principle is transferable to industrial autonomous assets that must blend onboard intelligence, remote coordination and changing operational modes.

Photonic-neuromorphic processing

Saffer et al. (2026) discuss Brillouin-based memory and signal processing for photonic neuromorphic computing, and Randel et al. (2026) describe optic-electronic-optic interferometric approaches for ultrabroadband arbitrary digital signal processing. Mondal et al. (2026) connect quantum-inspired neural processing with photonic IoT edge intelligence. In aggregate, the corpus suggests a hardware trajectory toward high-bandwidth, energy-conscious edge inference, but integration with scheduling and transferable skills remains underdeveloped.

Digital twins, reliability and maintenance

Mehdipour et al. (2026) synthesize digital twins, data management and AI for predictive maintenance, while Omoloja et al. (2026) emphasize implementation roadmaps for predictive-maintenance digital twins. Shao et al. (2026) show a neuromorphic computing framework combined with uncertainty-aware state estimation for fault detection. These works justify the inclusion of machine health, fault likelihood and uncertainty as active scheduling constraints. Pasupuleti (2026a) similarly frames AI for autonomous manufacturing, predictive maintenance and real-time quality assurance, supporting a system-level treatment of production intelligence.

Integration implication

The literature therefore contains strong components but only weak coupling across them. The research opportunity is to treat scheduling, skill transfer, event-driven sensing, photonic-neuromorphic execution and digital-twin constraints as one joint cyber-physical optimization problem. Pasupuleti (2026b) provides an additional conceptual bridge between topological photonics, neuromorphic computing and ultralow-power edge intelligence, reinforcing the plausibility of such cross-layer co-design.

Novel Architecture

The proposed architecture comprises: (i) a hybrid quantum-AI scheduling engine that encodes task, resource, precedence, energy, health and latency constraints; (ii) a transferable skill-representation layer that maps task semantics to shared latent primitives and robot-specific adapters; (iii) a photonic-neuromorphic perception layer

that produces sparse state events and confidence updates; (iv) a digital-twin constraint monitor that predicts machine/process state and exposes maintenance restrictions; and (v) a closed-loop execution controller that can trigger rescheduling or skill remapping when uncertainty, risk or resource state crosses configured thresholds. The distinguishing integration is bidirectional: perception and execution confidence alter schedule feasibility, while schedule decisions select and parameterize transferable skills.

Implementation

Module	**Illustrative implementation**	**Interface output**
Scheduler	Hybrid quantum-classical RL, QUBO/Ising mapping, quantum-inspired optimizer or classical fallback	task–robot assignment, start time, skill ID, confidence
Skill layer	latent skill graph, language-conditioned primitive library, policy adapter	robot-specific skill parameters and transfer fidelity
Perception	event camera, visuotactile sensor, photonic/neuromorphic processor	state event, uncertainty, contact/slip indicator
Digital twin	asset state, cycle model, maintenance/RUL model	availability, degradation, predicted constraint
Runtime assurance	constraint monitor, safe fallback policy, human override	allow/modify/reject action
Execution	robot controller and tool interface	completion state, quality result, observed energy/latency

Source--Art Landscape

Supplied source	**Relevant disclosed theme**	**Difference targeted by present disclosure**
Si et al. (2026)	Language-guided hybrid skill scheduling for embodied manipulation	Adds hybrid quantum-AI scheduling, photonic-neuromorphic event processing, digital-twin constraints and cross-platform latent skill adaptation in one feedback architecture.
Gu et al. (2026)	Hybrid quantum-classical reinforcement learning for scheduling	Extends scheduling output into robot skill selection/adaptation and execution-state feedback.
Bożejko et al. (2026)	Quantum computing and autonomous AI for flexible manufacturing scheduling	Adds transferable skills, neuromorphic perception and photonic edge processing.
Qiao et al. (2026)	Neuromorphic visuotactile slip perception	Uses perception events as variables that can invalidate or modify schedules and trigger remapping.
Chen et al. (2026)	Self-adaptive all-photonic synapse for autonomous neuromorphic robots	Uses photonic adaptation inside an integrated scheduling/skill-transfer/digital-twin control loop.
Liu et al. (2025)	Low-latency robotic instruction segmentation and scheduling over hybrid links	Generalizes latency into a joint scheduling, perception and skill-transfer constraint.
Mehdipour et al. (2026); Omoloja et al. (2026)	Digital-twin predictive maintenance	Feeds machine-health predictions directly into

		assignment and skill-execution feasibility.

Independent System

1. A cyber-physical industrial autonomous system comprising: a task and resource interface configured to receive production tasks and constraints; a hybrid quantum-AI scheduling processor configured to generate an assignment of tasks to a plurality of robotic resources using at least task precedence, resource availability and execution-state constraints; a transferable skill-representation module configured to select a shared robotic skill representation and transform the representation into an embodiment-specific skill for a selected robotic resource; a photonic-neuromorphic perception processor configured to generate event-driven state information from one or more industrial sensors; a digital-twin constraint monitor configured to estimate at least one machine-state, process-state or maintenance-state variable; and a runtime controller configured to execute the embodiment-specific skill and to cause rescheduling or skill remapping in response to a change in the event-driven state information, transfer confidence or digital-twin constraint state.

Independent Method

2. A computer-implemented method for controlling an industrial autonomous system, the method comprising: receiving a set of industrial tasks, robotic-resource states and operational constraints; generating, by a hybrid quantum-AI scheduling process, a candidate task-to-resource schedule; selecting a transferable skill representation corresponding to a task in the candidate schedule; adapting the transferable skill representation to an embodiment of a selected robotic resource; processing sensor events using a photonic-neuromorphic perception process to update an execution state; obtaining a predicted resource or process constraint from a digital twin; executing the adapted skill when a safety and feasibility condition is satisfied; and automatically modifying the schedule, adapted skill or both when a confidence, latency, maintenance, safety or energy condition crosses a threshold.

Dependent System

3. The system of claim 1, wherein the scheduling processor maps at least a portion of the scheduling problem to a QUBO or Ising representation and uses a classical fallback when a quantum resource is unavailable.

4. The system of claim 1, wherein the transferable skill representation comprises a graph of latent motion, force, perception and tool-interaction primitives.

5. The system of claim 1, wherein an embodiment-specific adapter is selected according to robot kinematics, payload, end-effector type and sensor configuration.

6. The system of claim 1, wherein neuromorphic visuotactile events indicating slip or contact instability cause immediate modification of skill parameters without waiting for a complete image frame.

7. The system of claim 1, wherein a photonic synaptic or photonic signal-processing element performs at least one temporal filtering, memory, classification or adaptive weighting operation.

8. The system of claim 1, wherein the digital twin outputs a remaining-useful-life or degradation variable used as a hard or probabilistic scheduling constraint.

9. The system of claim 1, wherein end-to-end communication latency is included as a cost or feasibility constraint for task assignment.

10. The system of claim 1, wherein a runtime-assurance module rejects a candidate schedule or skill when a predicted probability of constraint violation exceeds a threshold.

11. The method of claim 2, further comprising calculating transfer fidelity from a distance between a source skill embedding and an adapted target skill embedding.

12. The method of claim 2, further comprising triggering active sensing or rescheduling when state uncertainty exceeds an entropy threshold.

13. The method of claim 2, wherein schedule optimization jointly minimizes makespan, energy, latency, transfer error and operational risk.

14. The method of claim 2, wherein completed task outcomes update the skill representation for later transfer to another robotic resource.

15. The method of claim 2, wherein the schedule is recalculated after detection of machine degradation, tool failure, network degradation or a change in production priority.

16. The method of claim 2, further comprising generating an auditable explanation identifying which operational constraints caused task reassignment or skill remapping.

Recommended Scope

Before filing, a professional search should cover patent and non-patent literature for: hybrid quantum/classical job-shop and flexible-manufacturing scheduling; robotic skill libraries and cross-embodiment policy transfer; language-guided skill planning; neuromorphic tactile and visual control; photonic synapses and photonic neuromorphic accelerators; industrial digital-twin maintenance-aware scheduling; event-triggered rescheduling; QUBO/Ising manufacturing optimization; runtime assurance for adaptive robots; and integrated cyber-physical architectures combining these elements. Search claims and figures, not titles alone, and assess priority dates and family relationships.

2.1 Conceptual Framework

The conceptual framework assumes that industrial autonomy quality is a function of six interacting constructs: scheduling intelligence (S), transferable skill fidelity (T), neuromorphic perception responsiveness (N), photonic processing efficiency (P), safety/reliability assurance (R) and digital-twin fidelity (D). Scheduling creates feasible task-resource assignments; skill transfer maps task semantics to robot-specific action primitives; neuromorphic perception updates the state estimate from event-driven sensory changes; photonic processing accelerates selected transformations; safety and maintenance constraints prune unsafe actions; and the digital twin supplies predicted machine and process state. The expected outcome is not maximization of any single construct but a robust Pareto balance across throughput, energy, adaptation error and risk.

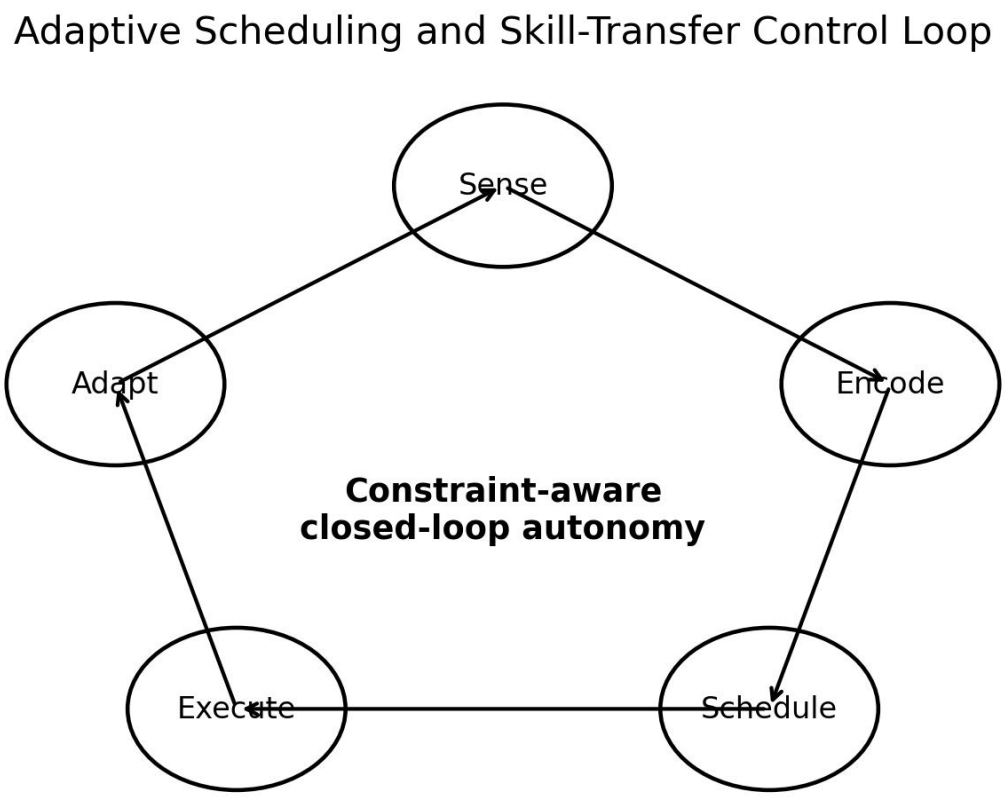

Figure 2. Closed-loop relationship among sensing, encoding, scheduling, execution and adaptation.

2.2 Research Gap

Gap dimension	**Observed gap in supplied corpus**	**HQ-PAST response**
Theoretical	Scheduling, skill transfer and neuromorphic perception are mostly treated as separable problems.	Defines a single cross-layer autonomy construct and coupled objective.
Methodological	Few models jointly include quantum-assisted scheduling, skill-transfer error, latency, energy and	Introduces multi-objective optimization plus state-space and probabilistic risk terms.

	reliability.	
Empirical	No common benchmark in the supplied sources evaluates the complete integrated stack.	Specifies ablation tests and measurable industrial KPIs for later validation.
Sectoral	Flexible manufacturing evidence is not consistently linked to heterogeneous robotic skill reuse.	Models robot–skill compatibility and machine/robot assignment jointly.
Implementation	Hardware acceleration, communications and digital twins are rarely co-optimized.	Defines explicit interfaces between photonic-neuromorphic edge, scheduler and digital twin.
IP/prior art	The source corpus describes component technologies rather than the exact integrated architecture proposed here.	Provides an invention disclosure while explicitly requiring formal patent-database searching before filing.

3. Methodology

This paper proposes a model-based analytical framework and uses numerical scoring for demonstration; empirical validation requires real-world data collection.The research design is constructive and systems-oriented.A future empirical implementation would sample tasks across assembly, handling, inspection and maintenance scenarios. Each task would be annotated with duration, deadline, precedence, required skill primitives, robot compatibility, expected energy, communication demand and safety class. Robot state would include joint and tool condition, sensor confidence, skill-embedding compatibility, estimated health and availability. The scheduler would be evaluated against classical heuristics and non-quantum RL baselines, while skill transfer would be assessed by adaptation time, success probability and residual error.

3.1 Mathematical Framework

Let tasks be indexed by i∈I, robots by r∈R, transferable skills by k∈K and discrete decision epochs by t. The framework uses assignment variables $x_i r$, skill-selection variables $z_i kr$, system state $s_t, action\ a_t$ and a learned/estimated risk function $\rho(s_t, a_t)$.

$J = w_1 C_m ax + w_2 E + w_3 L + w_4 \varepsilon_T + w_5 R - w_6 Q$ *(1)*

Equation (1) is the general objective. C_max is makespan; E is energy demand; L is decision/communication latency; ε_T is skill-transfer error; R is aggregate operational risk; Q is quality or task-success utility; and w1…w6 are non-negative weights.

$X = [x_i r], x_i r \in 0,1, \Sigma_r x_i r = 1$ *(2)*

Equation (2) is the assignment matrix. Each task is allocated to one robot, subject to compatibility and capacity constraints.

$s_(t + 1) = As_t + Ba_t + Ge_t + \xi_t$ *(3)*

Equation (3) is a dynamic state-space form. A represents system-state persistence, B the effect of control actions, G the effect of event-driven sensory inputs e_t, and ξ_t process uncertainty.

$h_k^* = argmin_h [d(h, h_k) + \lambda_1 C_p latform(h) + \lambda_2 C_s afety(h)]$ *(4)*

Equation (4) models adaptive skill transfer: a latent skill representation h_k is transformed to a target-compatible representation h_k* while minimizing representation distance and penalties for platform mismatch and safety constraint violations.

$\pi * = argmin_\pi E_\pi [\Sigma_t \gamma^t c(s_t, a_t)] subjecttoP(g_j(s_t, a_t) \le 0) \ge 1 - \alpha_j$ *(5)*

Equation (5) expresses risk-constrained sequential decision making. π is the scheduling/control policy, c is cost, γ is the discount factor, g_j are safety or resource constraints and α_j are allowed violation probabilities.

$R_t = 1 - \Pi_m (1 - p_m(s_t, a_t))$ *(6)*

Equation (6) aggregates multiple failure-mode probabilities p_m into a system-level risk indicator under a simplifying independence approximation.

$\eta_P N = Throughput/(Energy \times Latency)$ *(7)*

Equation (7) defines a photonic-neuromorphic efficiency index combining computational throughput, energy and latency.

$F_T = exp(-\beta ||h_source - M_r h_target||_2)$ *(8)*

Equation (8) defines transfer fidelity F_T, where M_r is a target-platform adaptation mapping and β controls sensitivity to embedding mismatch.

$H = -\Sigma_j p_j log p_j$ *(9)*

Equation (9) is an uncertainty/entropy measure that can trigger rescheduling when perception or skill confidence deteriorates.

$A_t = \sigma(\theta_0 + \theta_1 S_t + \theta_2 T_t + \theta_3 N_t + \theta_4 P_t + \theta_5 D_t - \theta_6 R_t)$ *(10)*

Equation (10) is a risk-adjusted autonomy-outcome predictor, where σ is a logistic transform and θ are estimated parameters in an empirical implementation.

$HQPAST = 0.22S + 0.20T + 0.16N + 0.14P + 0.16R + 0.12D$ *(11)*

Equation (11) is the illustrative composite score used below. The weights sum to 1 and can be changed through stakeholder, empirical or optimization-based calibration.

3.2 Numerical Model for Better Insight

Illustrative normalized values (0 = poor, 10 = excellent) are assigned solely to demonstrate calculation: $S = 8.8, T = 8.5, N = 8.9, P = 8.2, R = 9.1 and D = 8.4$. These numbers are not empirical observations.

Step 1: weighted scheduling contribution = 0.22×8.8 = 1.936. Step 2: skill-transfer contribution = 0.20×8.5 = 1.700. Step 3: neuromorphic perception contribution = 0.16×8.9 = 1.424. Step 4: photonic efficiency contribution = 0.14×8.2 = 1.148. Step 5: safety/reliability contribution = 0.16×9.1 = 1.456. Step 6: digital-twin fidelity contribution = 0.12×8.4 = 1.008. The total HQ-PAST score is 8.672/10.

Interpretation: within this illustrative configuration, the largest weighted opportunities for improvement are scheduling and skill transfer because they carry the highest weights and remain below the safety score. A system can therefore gain more from reducing rescheduling delay or skill-adaptation error than from marginally increasing already-high safety performance, provided that safety constraints remain satisfied.

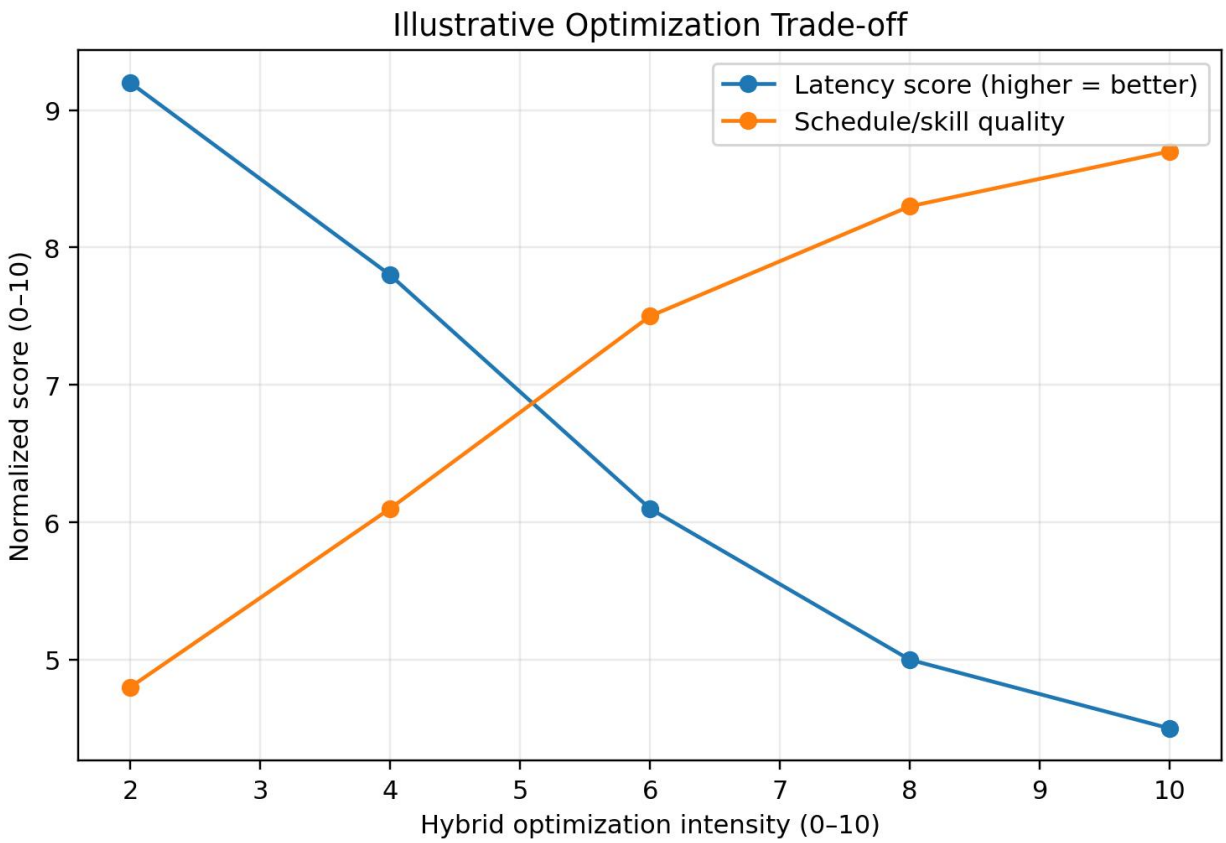

Figure 4. Illustrative trade-off between optimization intensity and normalized latency/schedule-quality scores.

3.3 Data and Variables

Variable	Definition	Scale	Expected effect	Relevance
S	Scheduling efficiency/quality	0–10 or objective-specific	Positive	Captures makespan, resource utilization and replan quality.
T	Cross-platform skill-transfer fidelity	0–10 / success rate	Positive	Measures reuse of learned manipulation across robots.
N	Neuromorphic perception	0–10 / ms	Positive	Represents event-to-state-

	responsiveness			update performance.
P	Photonic processing efficiency	0–10 / throughput-per-joule	Positive	Represents low-energy acceleration.
R	Safety and reliability assurance	0–10 / inverse risk	Positive	Penalizes unsafe or failure-prone plans.
D	Digital-twin fidelity	0–10 / prediction error	Positive	Represents accuracy of resource and process state.
L	End-to-end decision latency	milliseconds	Negative	High latency reduces adaptive autonomy.
E	Energy per completed task	joules or Wh	Negative	Supports energy-aware manufacturing.
ε_T	Skill adaptation error	continuous	Negative	Captures mismatch after transfer.
C_max	Makespan	seconds/minutes	Negative	Core production scheduling objective.
H	State uncertainty/entropy	continuous	Negative above threshold	Can trigger active sensing or rescheduling.

3.4 Proposed Model / Framework

The proposed model is named the Hybrid Quantum–Photonic Adaptive Skill Transfer (HQ-PAST) framework. It is intentionally modular: the scheduler may use a quantum, quantum-inspired or classical solver; the perception layer may use photonic-neuromorphic hardware where available; and the skill-transfer layer may be implemented using latent embeddings, demonstrations, language-conditioned primitives or policy adaptation. The novelty claimed at the research-framework level lies in cross-layer coupling rather than dependence on a single hardware technology.

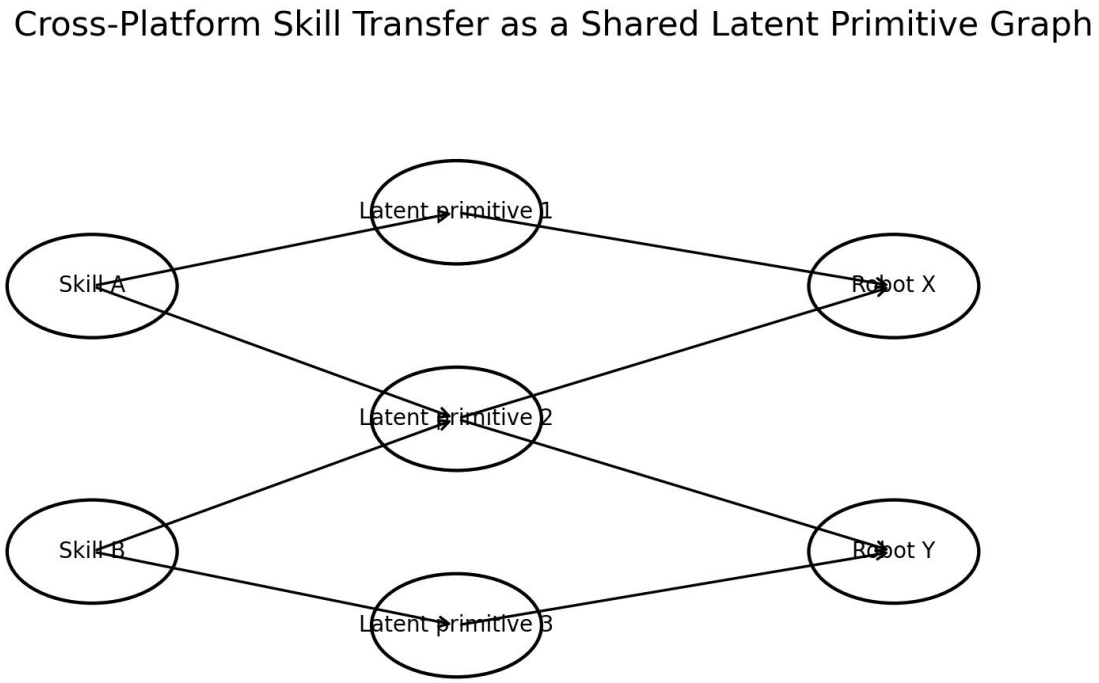

Figure 3. Shared latent skill primitives enable cross-platform transfer while preserving robot-specific adaptation.

4. Results and Analysis

Because empirical dataset is supplied, the results are analytical and scenario-based. They demonstrate internal implications of the proposed equations rather than measured industrial performance.

Scenario	**S**	**T**	**N**	**P**	**R**	**D**	**HQ-PAST score**
Baseline	6.8	6.2	6.9	6.1	8.2	7.0	6.82

classical modular stack							
Quantum-AI scheduling only	8.7	6.3	6.9	6.1	8.2	7.0	7.27
Scheduling + adaptive skill transfer	8.7	8.4	7.1	6.3	8.4	7.3	7.79
Full HQ-PAST illustrative stack	8.8	8.5	8.9	8.2	9.1	8.4	8.67

The scenario table indicates the system-level logic of integration. Improving only scheduling raises the composite outcome, but a larger improvement appears once transferable skills and event-driven perception are included. The full illustrative stack benefits from the interaction among scheduling, skill fidelity, neuromorphic responsiveness and reliability. This does not establish superiority in practice; it identifies the conditions under which an integrated architecture should be empirically tested.

Ablation logic further clarifies expected mechanisms. Removing the digital-twin layer should increase infeasible or maintenance-conflicting schedules. Removing the neuromorphic perception layer should increase contact-event reaction delay. Removing skill transfer should increase adaptation time whenever a task is moved to a different robot. Removing the hybrid optimizer should reduce flexibility in large constrained task-allocation spaces. These hypotheses are directly testable in a future robotic-cell experiment.

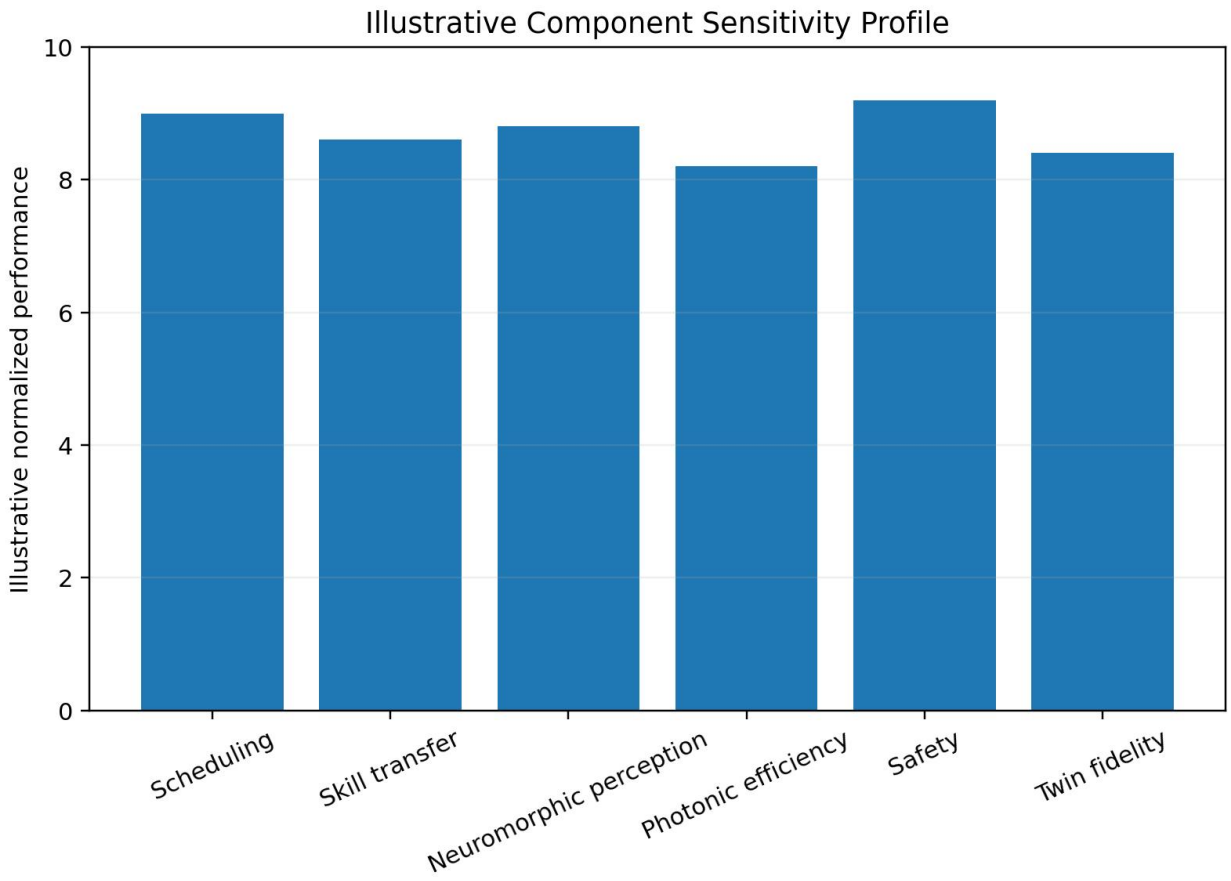

Figure 5. Illustrative sensitivity profile across HQ-PAST components; values are demonstrative, not measured.

Validation dimension	**Primary metric**	**Comparator**	**Expected test**
Scheduling	makespan, tardiness, utilization	dispatch rules / classical RL	same task set under dynamic disruptions
Skill transfer	success rate, adaptation steps, transfer error	retraining from scratch	cross-robot tool and geometry changes
Perception	event-to-action latency, false alarm rate	frame-based pipeline	slip/contact disturbance tests
Energy	joules per inference/task	electronic accelerator	matched workload and accuracy
Reliability	constraint	scheduler without	degraded machine-

	violations, failure probability	twin/health feedback	state scenarios
Resilience	recovery time after disruption	static schedule	machine outage, network degradation and tool fault

4.1 Discussion

The theoretical contribution is a cross-layer formulation in which scheduling and embodied intelligence share a common state and constraint representation. This differs from a pipeline in which a scheduler issues tasks and a robot controller independently attempts execution. In HQ-PAST, perception uncertainty and skill-transfer confidence can feed back to the scheduler, allowing a task to be reassigned or decomposed before failure.

The practical contribution is a deployment blueprint for flexible manufacturing. A factory could begin with classical optimization and electronic neuromorphic processing, then introduce quantum or photonic accelerators where they produce measurable value. This staged approach avoids making the architecture contingent on immature hardware and is consistent with the heterogeneous technological landscape represented by Gu et al. (2026), Bożejko et al. (2026), Chen et al. (2026) and Saffer et al. (2026).

For industry, the strongest value proposition is rapid reconfiguration: a robot can inherit a skill representation, adapt it to its embodiment, and receive a rescheduled work package after machine or demand changes. For maintenance, the digital twin can constrain assignments when health indicators deteriorate, linking predictive maintenance to production scheduling as motivated by Mehdipour et al. (2026) and Omoloja et al. (2026).

Technological implications include the need for standardized skill descriptors, timestamped state synchronization, confidence-aware sensor fusion and solver interfaces that expose constraints rather than opaque task IDs. The photonic-neuromorphic layer should be judged on end-to-end energy and latency under realistic workloads, not only device-level throughput.

Ethical and governance concerns include worker safety, explainability of machine reassignment, human override, data governance for demonstrations used in skill learning, cyber-physical attack surfaces and accountability for autonomous production decisions. The proposed architecture therefore treats safety as a hard or chance-constrained requirement rather than as an after-the-fact performance metric.

5. Conclusion

This paper develops HQ-PAST, a unified model for hybrid quantum-AI scheduling and adaptive robotic skill transfer within photonic-neuromorphic industrial autonomous systems. The framework integrates a high-level optimization layer, transferable latent skill representations, event-driven perception, photonic-neuromorphic processing, digital-twin state estimation and safety/maintenance constraints. Mathematical equations formalize assignment, dynamics, risk-constrained control, transfer fidelity, uncertainty and composite system performance. The illustrative numerical model demonstrates how system-level trade-offs may be quantified without misrepresenting the analysis as empirical proof. The central contribution is therefore architectural and methodological: it specifies what must be jointly optimized and how component technologies can exchange state, constraints and confidence information.

The framework is particularly relevant to high-mix manufacturing, autonomous inspection and maintenance, adaptive logistics and robotic cells subject to frequent reconfiguration. Its future value depends on empirical benchmarking against strong classical baselines, careful measurement of photonic-neuromorphic energy and latency, and robust safety validation. The invention-oriented disclosure below translates the research architecture into claim concepts for further professional patent drafting and formal prior-art review.

5.1 Limitations

The study is limited by the absence of a supplied empirical dataset, device measurements or robotic testbed results. Numerical scores are illustrative. The mathematical model abstracts complex hardware constraints, assumes measurable transfer fidelity and simplifies some failure dependencies. Quantum advantage is not assumed; a hybrid quantum-AI component must be compared with optimized classical

alternatives. Photonic-neuromorphic performance is likewise hardware- and workload-dependent. Generalizability across manufacturing sectors cannot be established until the framework is tested on multiple tasks, robots and operating conditions. Finally, the prior-art discussion is confined to the supplied academic corpus and is not a substitute for patent-database searching or legal patentability analysis.

5.2 Future Research Directions

- Benchmark hybrid quantum-classical and classical scheduling solvers under identical dynamic manufacturing constraints.
- Develop standardized robot-independent skill embeddings with embodiment-specific safety adaptation.
- Prototype photonic-neuromorphic event processing for tactile slip, tool-state and high-speed visual events.
- Couple remaining-useful-life uncertainty directly to task assignment and maintenance-aware production scheduling.
- Investigate formal verification and runtime assurance for transferred robotic skills.
- Test federated or privacy-preserving skill transfer across factories without exposing proprietary process data.
- Create multi-objective hardware-in-the-loop benchmarks covering latency, energy, safety, throughput and transfer accuracy.
- Perform a formal patent landscape and freedom-to-operate study across quantum scheduling, neuromorphic robotics, photonic synapses and skill-transfer architectures.

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