DESIGN OF AN INTEGRATED MONITORING SYSTEM FOR A FLOW-SHOP PRODUCTION LINE

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Abstract. *The paper proposes an integrated monitoring system for a household-appliance flow-shop line with 17 zones and 687 conveyors. A dedicated edge processing zone separates multi-rate acquisition and condition analysis from automatic process control. The design combines zone agents, redundant supervision, configuration-based network sizing and independent monitoring services. An eight-hour simulation compares reactive and alert-triggered maintenance under four matched injected degradations. Finished output rises from 25 to 198 units in this scenario. The comparison demonstrates the potential of early intervention, while metric-accounting limitations and the absence of field validation constrain its interpretation. A physical pilot is the next validation stage.*

Keywords: Flow-shop production; condition monitoring; edge computing; predictive maintenance; industrial simulation.

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1. Introduction

In a conveyor-connected flow-shop organisation, the impact of a defect depends on its position in the material flow. A stopped conveyor can block upstream stations and starve downstream operations. Machine monitoring therefore needs a line-level view of product movement, equipment condition and maintenance priorities. This information must remain available without delaying the control tasks that sequence production.

Condition-based maintenance connects data acquisition and processing to decisions about necessary interventions [1]. Digital manufacturing architectures use mechanisms that integrate physical resources with software services and enterprise information [2]. For an existing assembly line, the design problem is to make these mechanisms consistent across heterogeneous stations while maintaining the deterministic behaviour of the installed automation system.

This paper develops a monitoring structure for 17 production zones, separating control from edge processing and linking a configuration-driven communication model to executable monitoring functions. The architectural design is evaluated by

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help of a paired simulation experiment. The numerical results apply to the simulated scenario; industrial deployment and prognostic accuracy remain subjects for the physical pilot development.

2. Material and method

2.1. The production line and monitoring requirements

The studied case concerns a household-appliance assembly line with a nominal takt of 60 s, corresponding to one completed unit (final product) per minute under nominal operating conditions. Its 17 zones comprise 12 production stations, visual inspection, long-duration testing, two carrier-return sections and the finished-product warehouse. The transport system contains 687 conveyors. The product carriers travel in a closed loop, while approximately 7% of production enters a two-hour test branch. Figure 1 presents the main and auxiliary routes of the line model.

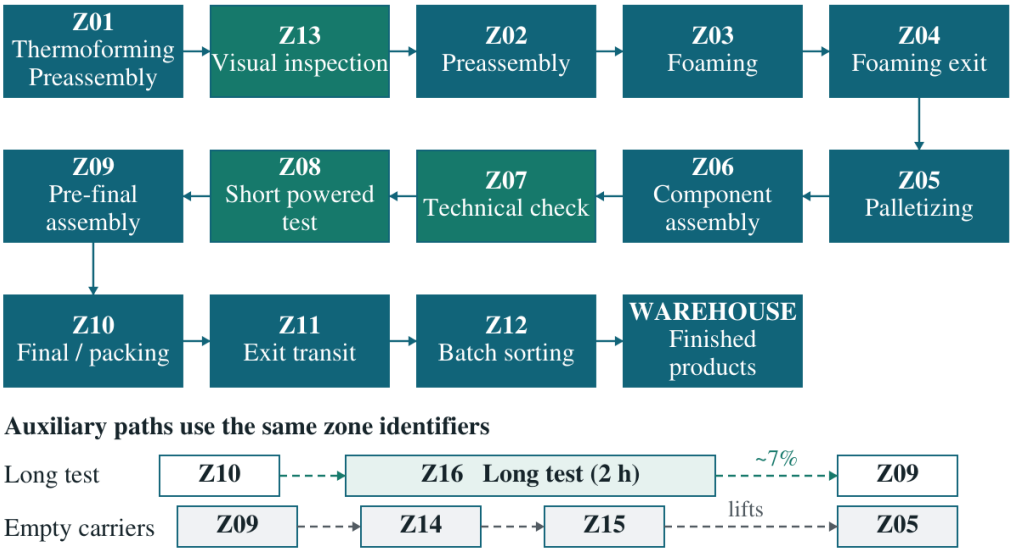

Figure 1. Production flow with auxiliary test and empty-carrier routes

These routes generate monitoring requirements beyond station alarms. The product identity must remain linked to the carrier, test verdict and processing history. The conveyor condition must be interpreted in the context of blocking and starvation states. The acquisition design must also accommodate dynamic force signals during active compliant product assembling with robots, slowly changing temperatures and discrete product-test events within the same zone interface.

The data acquisition configuration contains 67 distributed I/O islands and 2,296 monitored signals. A zone is the individual unit of instrumentation deployment; its signal registry defines the sensors, IoT gateways and aggregation nodes, sampling policies, limits and asset identifiers needed by the common monitoring services.

2.2. Functional architecture and control separation

The proposed monitoring architecture comprises seven functional layers L1-L7 at each workstation as shown in Figure 2. These are data-specific equipment layers. They are not fully mapped to the ISA-95 hierarchy: manufacturing execution (MES) and enterprise planning (ERP) are mainly related to the supervision of operations and batch planning domains described in IEC 62264-1 [3], although both are fed with current product and resource data collected at monitoring time.

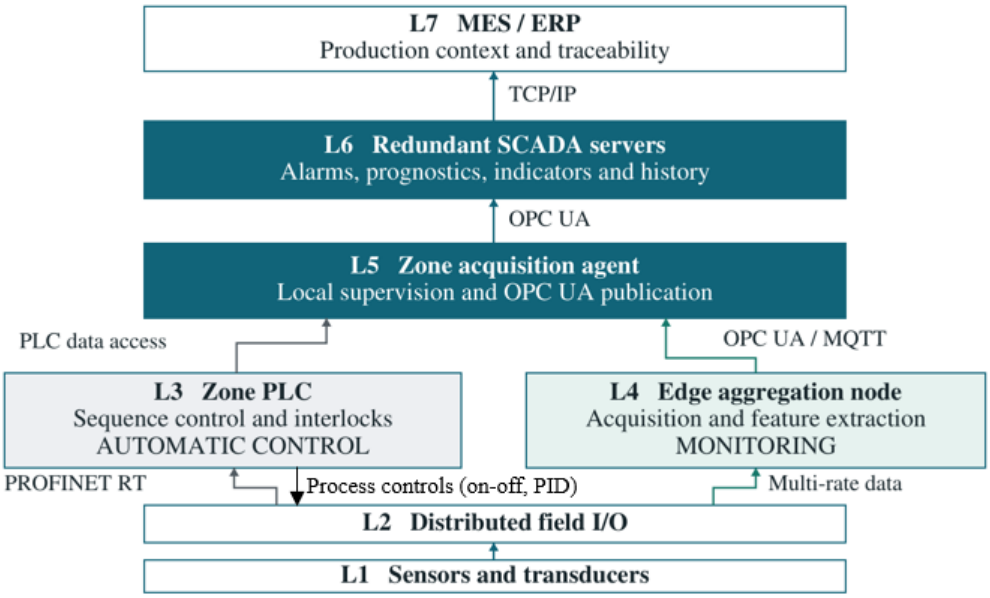

Figure 2. Seven equipment layers with parallel control and product monitoring paths

Distributed sensors feed I/O zones (IoT gateways) on L1, L2 layers. The PLC zone on L3 layer executes operation sequencing, actuating commands and interlocks based on collected process data, while the L4 edge aggregation node performs condition-data acquisition, alignment and preprocessing. The L5 industrial PC layer combines process context and product features (retrieved from L4) with control data and PLC status (retrieved from L3) and exposes an OPC UA interface to the L6 supervisory servers [4]. L7 provides order, planning and traceability context.

The parallel branches require an explicit data-access mechanism. Compatible shared-input configurations [5] and dedicated acquisition channels supply monitoring data while preserving control ownership. An backup process controller (PLC) can be added to ensure fault tolerance by passive hardware redundancy. The reads must be bounded, and monitoring services have no priority over safety

functions or actuator commands; process control is thus decoupled from production line monitoring (resources, products, real time product execution orders).

2.3. Edge acquisition and station-specific processing

A dedicated edge node is proposed for each zone (Table 1). Its tasks are multi-rate acquisition, time alignment, primary processing and local buffering. Samples retain source timestamps, engineering units, quality status and asset identifiers. IEEE 1588 provides the clock-synchronization framework [6]; the actual timestamp accuracy depends on the acquisition hardware and network configuration. Resampling a signal must add to previous acquisition operations for trend estimate.

Table 1. Two instances of the common edge processing structure

Station	Measurements	Edge outputs
Robotic assembly. Two ABB IRB 6700 robots	Two insertion-force channels; 250 Hz bursts; four joining points	RMS force and force–insertion depth envelopes
Robotic assembly	Vacuum, encoders and robot states	Cycle context and drift events
Product testing	Earth continuity, insulation, dielectric strength, leakage current and power	Five test results linked to each unit
Product testing	Gas-leak event; thermocouples at 1 sample/s in 16 test positions	Alarm events, temperature history and unit verdict

At assembly cell level, root-mean-square values and insertion envelopes summarize each operation. An exponentially weighted moving average (EWMA) tracks changes in these features over successive cycles. A force trace becomes useful for wear monitoring only when comparable joining operations are aligned by cycle and position; mixing different products or insertion depths can generate a misleading trend.

At the test station, the edge node associates the sequence and verdict of each test with the product identifier. The proposed 50 ppm gas-leak event threshold is an engineering setting requiring confirmation for the detector, gas and test procedure. However, It is not a universal acceptance limit for household appliances.

Raw bursts and low-rate histories serve different purposes. At 250 Hz the Nyquist frequency is 125 Hz, so this configuration cannot support every bearing-vibration diagnostic. Higher-frequency analysis requires suitable sensors, anti-aliasing and faster acquisition. Local buffering retains records during an uplink outage; forwarding resumes with source timestamps and duplicate handling. Event-

triggered raw bursts need a retention policy separate from the one-second supervisory history.

2.4. Communication topology and availability

The proposed network combines local PROFINET rings with a redundant Ethernet core (Figure 3). Each zone has a separate subnet, 10.40.N.0/24, and VLAN 100+N, for N from 1 to 17. Addresses .10, .11 and .12 respectively identify the PLC, acquisition agent and edge node; field-I/O addresses start at .21. The core occupies VLAN 100.

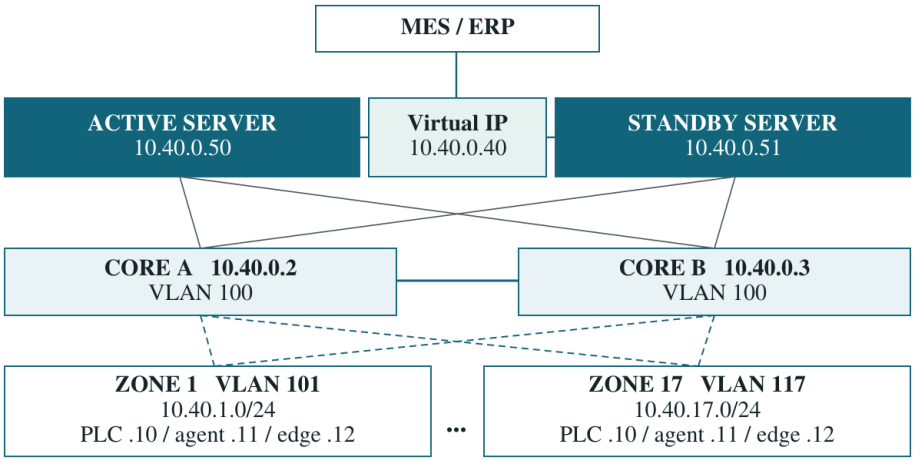

Figure 3. Logical network topology with redundant core paths and zone subnets

The control path has a configured PROFINET IO RT cycle of 4 ms. MRP provides ring recovery for its specified single-failure cases [7]. The design uses a recovery target below 200 ms and a supervisory server takeover value of approximately 1.8 s through virtual address 10.40.0.40. These values require hardware measurements; they are not established as field results. Ring recovery can interrupt traffic, so watchdog settings are assessed independently of the normal cycle time.

Redundant servers, core paths and UPS units improve availability, but individual sensors, PLCs and edge nodes remain possible local failure points. Dual attachment requires supported interfaces and a configured loop-prevention or redundancy mechanism. VLAN separation also requires access restrictions and authenticated communication to contribute to the security objectives of IEC 62443 [8].

2.5. Equipment and data-volume sizing

Table 2 summarizes the proposed equipment classes. The common structure is instantiated per zone, with an S7-1214C exception at visual inspection. The edge hardware remains a pilot selection. Network roles, interface counts and firmware compatibility were checked for the selected devices. The data acquisition and monitoring timing is presented in Table 3.

Table 2. Principal equipment in the proposed deployment.

Function	Candidate equipment	Quantity
Supervisory servers	Dell PowerEdge R650, active and standby	2
Core switches / UPS	SCALANCE XM416-4C / APC SRT 3000 VA	2 / 2
Zone acquisition agents	SIMATIC IPC427E	17
Edge aggregation nodes	Industrial acquisition PC with PTP	17
Zone PLCs	S7-1516-3 PN/DP; one S7-1214C exception	17
Zone switches	SCALANCE XC208	17
Distributed I/O islands	ET200SP, IM155-6 PN HF	67

Table 3. Acquisition classes and supervisory retention.

Data class	Acquisition policy	Retention or output
Fast process data	25–250 samples/s, including bursts	Features and selected raw bursts
Equipment values	Typically 1 sample/s	1 s history for 2 h; 1 min aggregates for 24 h
Slow or state data	Several seconds or on change	Configured values and transitions
Events / genealogy	On occurrence	Complete event records and archives

The registry-based estimate is 537 published samples/s and approximately 344 kbit/s at the server. Their ratio implies about 80 bytes per published sample, including the assumed record overhead. This is an effective published rate, not the simultaneous sampling of all 2,296 signals. Burst concurrency, protocol framing and reconnection traffic require separate capacity allowances.

The stated historian estimate is approximately 371 MB/day. It is interpreted with the retention policy: continuously saving 344 kbit/s would instead require about

3.72 GB/day. Aggregation and storage encoding explain why traffic and retained volume require separate calculations. The baseline address registry contains 107 static entries; adding 17 edge nodes gives 124 entries before any additional management addresses.

2.6. Monitoring functions and decision support

For each parameter, the acquisition produces a time-stamped sequence at its configured rate. Quality checks precede interpretation: an absent or invalid sample must be marked unavailable. For a valid value x, instantaneous conformity is defined by the permitted interval [L, H]:

$$v(x) = 1 \; if \; L \leq x \leq H; \quad v(x) = 0 \; otherwise. \tag{1}$$

The prototype adds a 3 s persistence delay and a 2% deadband to suppress transient and chattering indications. The deadband reference have been configured per signal. These are application settings; alarm-management standards specify a lifecycle for alarm design and response [9], which represent dedicated values for these parameters.

$$z_t = \lambda x_t + (1 - \lambda) z_{t-1}, \quad z_0 = \mu. \tag{2}$$

$$|z_t - \mu| > k\sigma\sqrt{\frac{\lambda}{2-\lambda}}, \quad \lambda = 0.2, \; k = 3. \tag{3}$$

Equations (2, 3) implement Exponentially Weighted Moving Average (EWMA) drift detection with the asymptotic control limit [10]. The reference mean μ and standard deviation σ must come from representative healthy operation. Auto-correlation, startup transients and changes of recipe affect false-alarm behaviour and therefore require calibration.

$$s = 100 \, clip_{[0,1]}\left(1 - \frac{x - x_{nom}}{x_{crit} - x_{nom}}\right). \tag{4}$$

$$RUL = max\left(0, \frac{x_{crit} - x_{now}}{a}\right), \quad a > 0, \; R^2 > 0.3. \tag{5}$$

The subscripts nom, crit and now denote nominal, critical and current values. The health score in (4) is clipped to [0, 100] for increasing degradation with a critical value above the nominal value. Equation (5) extrapolates a fitted positive slope a. The $R^2 > 0.3$ rule is a prototype eligibility check, not a confidence guarantee. Unstable trends require an unavailable estimate. ISO 13374 provides the broader processing framework [11].

$$OEE = A \cdot P \cdot Q. \tag{6}$$

Availability A, performance P and quality Q require a common asset boundary and accounting period [12]. Recommendations concern parameter adjustment, maintenance timing or component replacement. Each intervention remains subject to the authorized maintenance and control procedures; a predicted remaining life does not itself authorize a control action.

2.7. Monitoring software

The software mirrors the monitoring path through a publish-subscribe event bus (Figure 4). Zone sources publish samples, cycle records and events. Independent services compute alarms, health estimates and production indicators or maintain history. The operator interface navigates from the line map to station and signal detail, following the HMI design framework of ISA-101 [13].

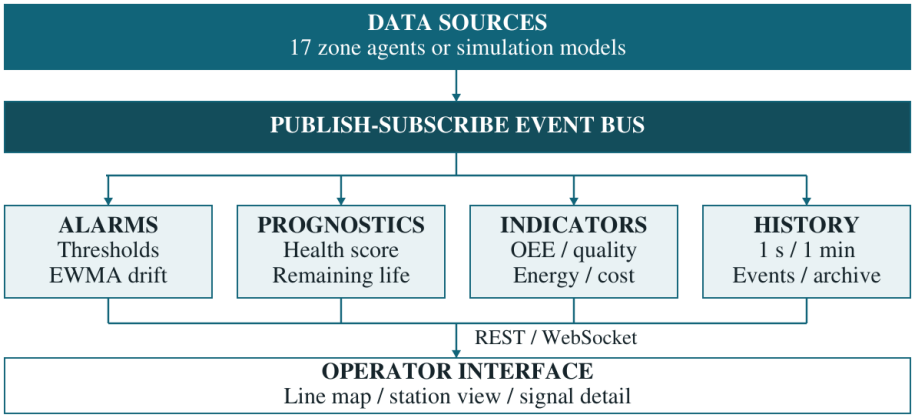

Figure 4. Monitoring services and operator access through a common event interface

Failure isolation depends on bounded queues, independent execution and explicit retry policies. Publishing alone does not guarantee service independence. The data contract preserves the source time, sequence identifiers and quality flags through buffering and replay. Replacing simulator sources with industrial adapters can then preserve the service interfaces, although timing, security and hardware integration still need commissioning.

2.8. Simulation protocol

The proposed simulation represents the complete line, including degradation and injectable faults. Structural checks cover all 17 zones and the generated equipment and address configuration. The paired maintenance experiment uses an eight-hour horizon, the same random seed and the same four injected degradations. Policy A

intervenes after failure, with modelled corrective durations of 90–180 min. Policy B intervenes at the first monitoring alert, with planned durations of 15–30 min.

The comparison combines earlier intervention with shorter assumed repairs; it does not isolate prediction accuracy. A matched seed improves comparability. Statistical evaluation requires repeated scenarios, equivalent initial work in progress and exported event logs.

3. Results and discussion

Table 4 reports the paired simulation outcome. The finished output increases by 173 units from 25 to 198, which is a 692% relative increase over the severely disrupted reactive case. Unplanned stoppage falls by 159 min. These values support the operational relevance of acting before an injected fault blocks the flow; they do not establish an expected industrial improvement of the same magnitude.

Table 4. Eight-hour reactive and alert-triggered maintenance scenario.

Indicator	Reactive A	Predictive B	Difference
Finished units	25	198	+173 (+692%)
Reported OEE indicator	43.0%	53.6%	+10.6 pp
Unplanned stoppage	159 min	0 min	−159 min
Reported maintenance time	546 min	~90 min	~456 min lower
Modeled losses	19,666 RON	3,780 RON	−15,886 RON

The OEE values require an explicit accounting definition. With the usual common-boundary decomposition, OEE reduces to good output multiplied by ideal cycle time and divided by planned production time. If 60 s is treated as the ideal cycle and the full 480 min as planned time, the two finished-unit counts correspond to 5.2% and 41.3%, respectively. They therefore cannot independently reproduce the reported 43.0% and 53.6%. Different asset aggregation, production-time exclusions or counters may explain the discrepancy, but the event records and component factors are required to determine which interpretation applies.

The 546 min maintenance entry also exceeds the eight-hour observation horizon. It cannot represent non-overlapping elapsed downtime of the whole line within that shift. Its resource and time basis must be reconciled before interpreting the approximate 6.1:1 ratio as an operational saving. The cost difference is approximately 80.8% of the reactive loss, but remains a result of the simulation cost

model. Accounting calibration and implementation costs are outside this comparison.

The structural result is narrower: the configured architecture was checked across 17 out of 17 zones. This supports reuse of the zone pattern. It does not validate field timing, fault diagnosis or prognostic calibration. The next experiment will record alarm lead time, missed and false alerts, maintenance intervals and product-flow events over repeated scenarios, followed by a shadow-mode pilot on the robotic assembly station.

4. Conclusions

The proposed system organizes line monitoring around a common zone interface and a dedicated edge path. The simulation illustrates how early maintenance can preserve flow under injected degradation, while the metric-accounting issues limit quantitative conclusions. A physical pilot must establish timing, sensing adequacy and prediction quality. Further development will associate assets with Asset Administration Shells [14] and map resource, product, order and expert roles to a holonic structure [15]. These extensions should preserve control ownership and make condition information traceable to the monitored resource and product.

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