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Design and Analysis of Machine Downtime Reduction Using Simulation and Modeling Methods

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Abstract

Particulate contamination on end effectors (EE) in hard disk drive (HDD) precision assembly can trigger frequent cleaning, adding non-value-added downtime and increasing post-maintenance alignment variability, particularly at bottleneck operations. Conventional offline ultrasonic cleaning requires tool stoppage, component removal, transport, drying, reassembly, and process requalification, extending effective downtime. This study proposes and numerically evaluates an in-machine Auto Self-Cleaning (ASC) concept to reduce cleaning-induced downtime while maintaining process stability. Lean-based root-cause analysis was applied to prioritize downtime drivers and translate them into functional design requirements. The proposed concept integrates an air-jet purge strategy within a dedicated cleaning chamber combined with vacuum-assisted extraction. Computational Fluid Dynamics (CFD) was used to iteratively refine chamber geometry and airflow behavior to improve purge coverage and reduce particle re-deposition risk. Simulation results indicated a 98.89% particle-collection ratio under representative boundary conditions. By eliminating major offline cleaning steps, downtime per cleaning event was projected to decrease from 85 minutes to 15 minutes, corresponding to an 82.4% reduction. Beyond mechanical and CFD-based optimization, the ASC architecture provides a scalable foundation for smart-manufacturing integration through IoT-enabled monitoring, predictive maintenance strategies, and data-driven optimization aligned with Lean and TPM principles. The proposed framework enhances equipment availability (OEE), operational robustness, and long-term manufacturing resilience in high-precision HDD assembly environments.

Keywords
Hard Disk Drive, Automation, Auto Self-Cleaning, Lean manufacturing, Downtime

1. Introduction
Hard disk drives remain a cornerstone of large-scale data storage infrastructure particularly in hyperscale data centers because they continue to offer a strong cost-per-terabyte advantage for many enterprise applications. Sustaining this advantage relies on ongoing advances in density scaling captured in industry roadmaps and technical outlooks. In high-volume manufacturing, these gains depend on highly automated precision-assembly systems operating under tight tolerances and strict contamination-control requirements, where even small particulate levels can elevate malfunction risk and degrade quality.

From a Lean Manufacturing perspective, cleaning and maintenance are non-value-added when they do not directly create customer value; however, in high-precision HDD assembly they become unavoidable due to contamination risk. Repeated platter pick-and-place operations can promote particle and residue accumulation on end-effector contact regions, increasing cross-contamination probability across subsequent platters and reducing process cleanliness, as shown in Figure 1. The prevailing mitigation approach is offline ultrasonic cleaning, where cavitation effectively removes adhered contaminants (Holimchayachotikul and Laosiritaworn 2008). In practice, this workflow often exceeds the planned preventive maintenance (PM) window because it requires tool stoppage, component removal, transport to a cleaning area, cleaning/drying, reinstallation, and post-maintenance verification, resulting in recurrent capacity loss. Moreover, repeated disassembly and reassembly can introduce recovery variability and alignment sensitivity when positioning depends on re-locating or manual adjustment rather than robust locating features (Figure 1).

To address this gap between intended PM duration and actual cleaning time, this study applies Fishbone analysis to structure and prioritize the drivers of particle accumulation and extended downtime. In parallel, CFD-based airflow modeling is used to evaluate and optimize design-stage changes such as in-machine cleaning and process redesign to reduce particle retention and cleaning burden prior to physical iteration (Wu et al. 2017)

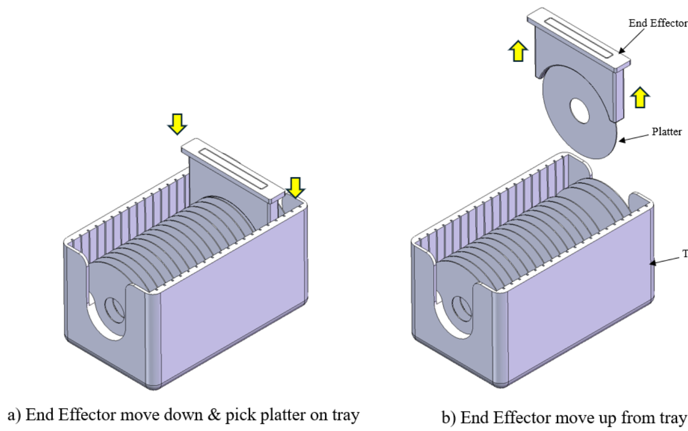


Figure 1. End Effector movement

1.1 Objective

This study aims to develop an in-machine air-jet purge concept and numerically assess its particle-removal potential using CFD under HDD assembly constraints. The concept targets the replacement of conventional offline ultrasonic cleaning by reducing major non-value-added activities and associated cleaning-related downtime at bottleneck operations. The redesigned EE cleaning approach is intend to remove particulate contamination without disassembly and to mitigate post-service alignment variability and recovery time. The study further defines simulation-informed design criteria and measurable manufacturing indicators for subsequent on-tool verification, including cleaning cycle time, downtime per cleaning event, residual particle contamination, and post-cleaning alignment stability.

2. Literature Review

Lean manufacturing is widely applied to improve operational performance by eliminating non-value-added (NVA) activities and strengthening value-stream flow. In high-precision industries, Lean is often reinforced through Total Productive Maintenance (TPM) to stabilize equipment performance and reduce variability at critical processes. However, in HDD manufacturing, particulate contamination is a critical risk in automated assembly environments, and cleaning-related tool stoppages can become a major source of lost capacity (McKone et al. 2001; Cua et al. 2001; Swanson 2001; Anh and Matsui 2012; Achouch et al. 2022). Contamination control is a key yield driver in HDD production, commonly managed through controlled environments and offline cleaning methods.

Ultrasonic cleaning is recognized as effective for removing small/submicron particles under suitable conditions, but an offline workflow that requires repeated removal and reinstallation can introduce maintenance induced variation and longer recovery especially when components operate under micro-scale tolerances. CFD supports virtual evaluation of airflow patterns and contamination behavior to refine contamination-mitigation designs before fabrication, including HDD cleanroom contexts (Metzger and Mehring 2024; Sharma et al. 2022; Biswal et al. 2024; Wu et al. 2017). For purge-based concepts, purge-air configuration and flow field details can strongly influence particle-trajectory behavior and contamination protection performance. Literature rarely combines Lean diagnostics, Fishbone diagram root-cause structuring (Watson and Spiridonova 2019) and CFD-guided hardware refinement into one end-to-end framework, motivating the development of an ASC module for HDD assembly (Naosungnoen and Thongsri 2018a, 2018b; Thongsri 2017; Thongsri 2021; Chakraborty 2024).

3. Methods

In high-precision HDD assembly, contamination-related maintenance can force tool stoppage and reduce equipment availability. This study addresses this downtime mechanism by proposing an Automated Self-Cleaning (ASC) concept based on an air-jet purge with vacuum extraction, which is intended to restore end-effector cleanliness without the extended offline ultrasonic workflow.

A Fishbone diagram is used to identify and prioritize root causes of frequent stoppages, translating contamination drivers into functional requirements for the embedded cleaning module. Based on these requirements, a cleaning chamber and purge/extraction configuration are designed in SOLIDWORKS. CFD is then applied to evaluate airflow behavior and particle-transport tendencies within the chamber. Key parameters such as nozzle orientation, purge velocity, extraction routing, and chamber geometry are iteratively refined to improve purge coverage and to reduce low-velocity zones and potential particle re-deposition risk.

The output of this phase is a simulation-informed design proposal and a set of evaluation metrics planned for subsequent experimental validation, including cleaning-related downtime, particle-removal performance, and post-maintenance alignment stability. Overall, the study provides a proposed roadmap for embedding self-cleaning capability into high-precision HDD assembly to strengthen productivity and operational robustness.

3.1 Current-State Characterization and Problem Definition

The existing platter-handling EE cleaning workflow was characterized through direct shop-floor observation, repeated time measurements, and review of relevant maintenance and process documentation. The offline ultrasonic cleaning routine was mapped and decomposed into discrete activities, including equipment stoppage, EE removal, transportation to the cleaning room, ultrasonic cleaning, drying, reassembly, and process qualification/buy-off, as presented in Figure 2. Step-level durations were recorded across multiple cleaning events and aggregated to quantify baseline performance, with downtime per event defined as the primary metric capturing the effective production loss attributable to each cleaning cycle. Total cleaning cycle time was also computed to provide additional insight into the full maintenance workload and to identify dominant time contributors within the routine. In addition, the operational impact at the bottleneck workstation was assessed based on observed flow interruptions associated with these cleaning events.

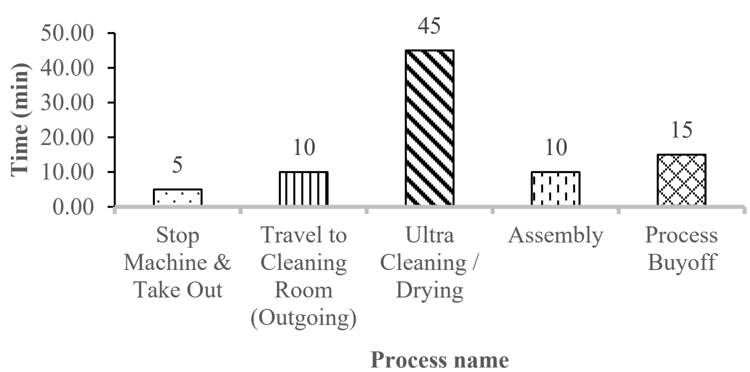


Figure 2. Process Downtime Ultrasonic Cleaning

3.2 Cause-Structure Analysis Using Fishbone diagram

A Fishbone diagram was used to systematically identify and structure the main contributors to high machine downtime caused by frequent cleaning and prolonged recovery. Potential causes were grouped using the 4M framework Method, Machine, Man, Material, as shown in Figure 3. To support root-cause analysis and prioritize improvement actions (Figure 3).

- Method: reliance on an offline cleaning procedure, a long verification/buy-off sequence after cleaning, cleaning intervals fixed by PM, and the absence of a standardized “quick-clean” cycle together extending the end-to-end downtime per event.
- Machine: cleaning requires stopping and opening the tool, limited access to cleaning points, dust/particle trapping zones, inefficient airflow/purge paths, and no built-in self-cleaning capability making contamination removal slow and less effective.
- Man: downtime increases due to staffing-dependent response time, manual cleaning effort, operator-to-operator skill variation, and setup/alignment re-check requirements after removal/reinstallation.
- Material: recurring contamination sources such as particle/residue generation, film build-up on contact surfaces, consumable shedding, and high sensitivity to contamination driving repeated cleaning demand.

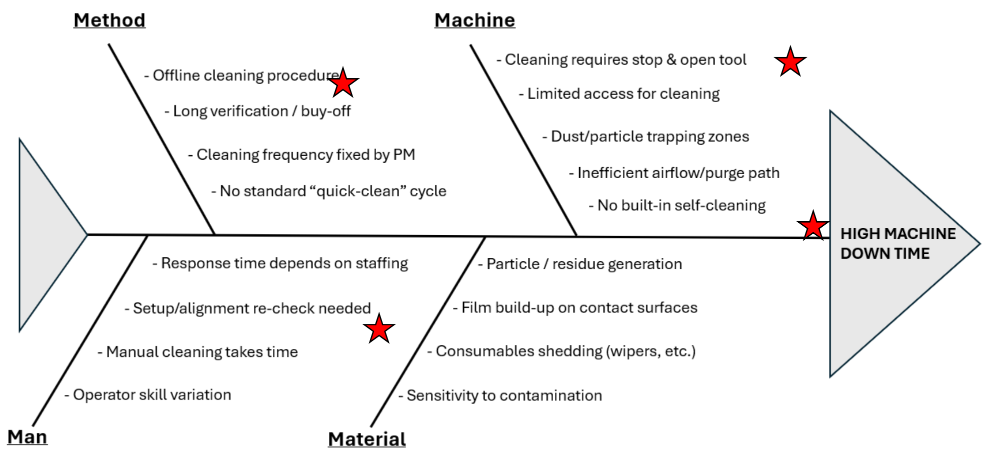


Figure 3. Fishbone diagram

3.3 Translation of Root Causes into Design Requirements

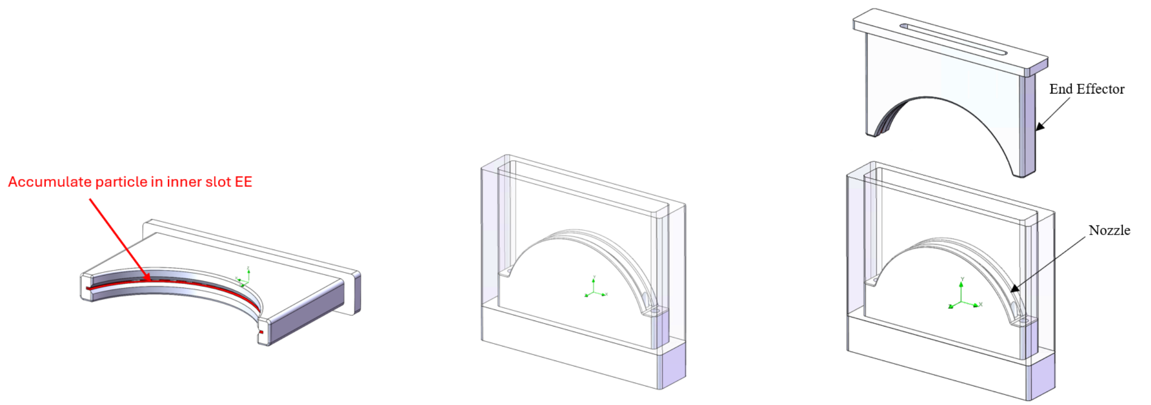
Based on the fishbone-selected drivers offline cleaning procedure, long verification/buy-off, cleaning that requires stopping and opening the tool, absence of built-in self-cleaning, and repeated setup/alignment re-check these root causes were translated into concise, verifiable design requirements. The solution shall enable in-machine cleaning to eliminate offline removal and reduce the number of handling steps, while minimizing tool stoppage by avoiding open-tool maintenance whenever possible. A built-in self-cleaning capability shall be integrated as a standard function of the workstation, with controlled purge/extraction features to restore cleanliness within the normal operating sequence. To address extended recovery, the design shall shorten verification and buy-off time by providing repeatable, condition-based acceptance criteria and reducing dependence on manual judgment. Finally, the system shall incorporate robust locating and constraint features to preserve positional repeatability after maintenance, thereby minimizing or eliminating the need for setup and alignment re-check during service recovery.

3.4 Concept Development for Cleaning Related Downtime Reduction

A cleaning chamber was designed to create a controlled boundary around the EE so contamination can be removed rapidly with minimal process cleaning downtime by combining an air-jet purge and vacuum extraction within a single integrated module. Using SolidWorks for 3D development, the chamber geometry was modeled to closely follow the EE working envelope to minimize leakage paths while maintaining safe mechanical clearance for motion, and to provide a defined internal flow corridor that forces purge air to sweep across contamination-prone EE contact and leading surfaces. Purge ports (nozzles or slots) were positioned and oriented to generate high local shear along critical regions to detach adhered particles, while strategically located vacuum ports downstream established a dominant pressure gradient to capture and evacuate released contaminants immediately, reducing re-deposition and preventing particle escape into surrounding machine zones. The CAD concept emphasized manufacturability and integration by incorporating mounting interfaces, sealing features, and modular port inserts to enable fast iteration of nozzle orientation and extraction locations without redesigning the full chamber. This boundary-based chamber was intended to convert cleaning from a lengthy manual/offline activity into a short, repeatable in-machine routine, directly targeting reductions in downtime per cleaning event while preserving assembly constraints required for high-precision operation

3.5 CFD Analysis of Cleaning-Chamber Airflow

Flow Simulation was used to evaluate vacuum-assisted airflow behavior inside a cleaning chamber under a single purge strategy intended to improve sub-micron contaminant removal. Particle accumulation within the inner EE slot used for platter pick-and-place, as shown in Figure 4(a), was used to define the primary region of interest for airflow assessment and to guide the chamber boundary design around critical contact and near-contact surfaces. A 3D CAD model of the cleaning chamber, as shown in Figure 4(b), was developed in SOLIDWORKS, and an internal flow project was defined to represent the enclosed flow domain and the connected purge and exhaust passages, as shown in Figure 4(c). In the selected operating configuration, purge air was applied only at the chamber nozzle locations and extracted through a vacuum outlet, representing a chamber-only purge with vacuum-assisted removal. For all simulation cases, the exhaust boundary was specified as a vacuum outlet condition to represent vacuum-assisted extraction, and all chamber surfaces were treated as solid walls consistent with the default no-slip assumption for internal flow in Flow Simulation. Global project settings and boundary definitions were held constant across simulation runs to ensure consistency, with the chamber-only purge arrangement and vacuum extraction serving as the fixed operating mode for airflow evaluation.



a) End Effector accumulate particle   b) New Design Chamber Cleaning   c) End Effector Cleaning with New Chamber

Figure 4. Chamber Auto Self-Cleaning

The computational domain was discretized using the internal-flow meshing scheme in SOLIDWORKS Flow Simulation, with local mesh refinement applied in regions expected to govern cleaning effectiveness, including nozzle exit planes, jet–surface impingement zones on the chamber and EE surfaces, and the vicinity of the vacuum outlet, as shown in Figure 5. Mesh independence was assessed using at least two mesh densities by comparing solution stability and key flow metrics to confirm that the observed trends were not artifacts of discretization.

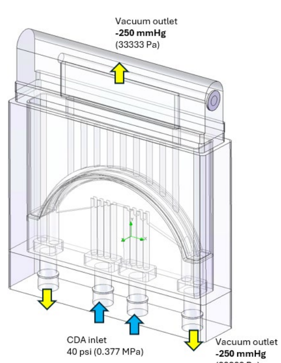
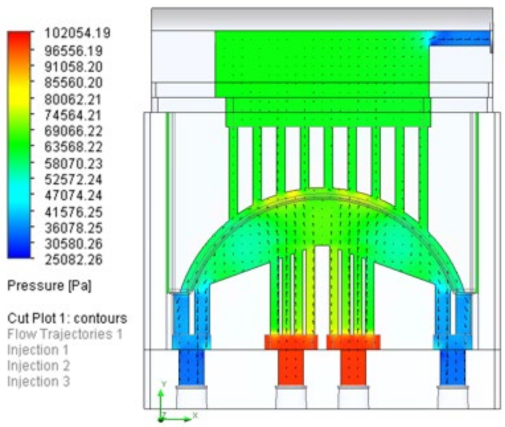
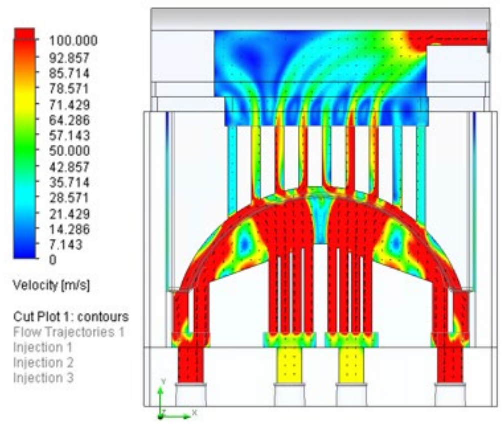


Figure 5. Solution Cleaning End Effector

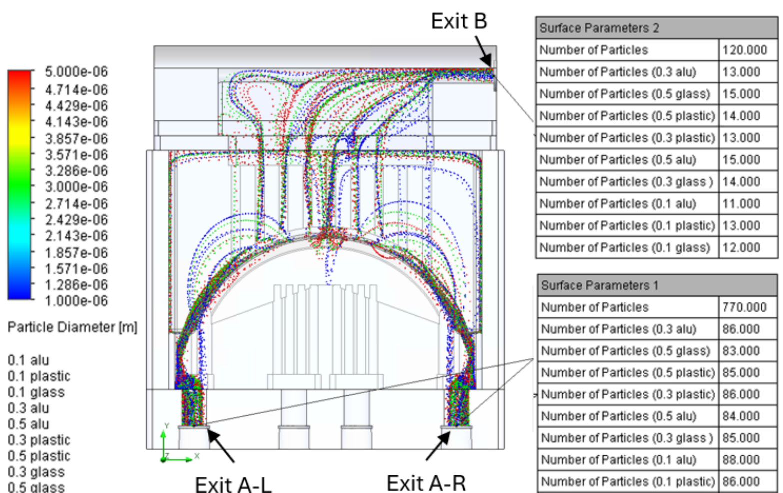
The numerical study was organized into three coupled analyses. A pressure-field analysis was first conducted to establish the extraction-driven pressure distribution within the enclosed chamber and along the purge–exhaust passages under fixed boundary definitions, as shown in Figure 6(a). A velocity-field analysis was then performed to characterize airflow structures relevant to cleaning performance, with emphasis on purge-jet development, near-wall flow behavior, and transport pathways toward the outlet, as shown in Figure 6(b). Finally, a particle-transport analysis was carried out to evaluate sub-micron contaminant removal: particles were released from the inner EE slot (the critical pick-and-place region), considering three particle materials (aluminum, plastic, and glass). For each material, three particle diameters (0.1 µm, 0.3 µm, and 0.5 µm) were simulated under identical purge and extraction boundary conditions, varying only particle size and material to isolate their effects on transport behavior, as shown in Figure 6(c). Removal performance was quantified using the particle count collected at the vacuum outlet as the primary comparison metric across all cases



a) Pressure Simulation



b) Velocity Simulation



c) Particle Simulation

Figure 6. Flow Simulation Chamber Cleaning

Results were interpreted based on CFD-only evidence from Flow Simulation post-processing outputs, including velocity and pressure contour plots and streamline visualizations, to indicate dominant extraction pathways toward the vacuum outlet. These outputs were used to locate recirculation structures and low-velocity regions near critical surfaces that could have increased particle residence time and could have elevated re-deposition risk. The interpretation focused on flow coverage around the inner EE-slot region of interest, the continuity of transport toward the outlet, and the presence of stagnant zones. In addition, a particle-tracking analysis within the simulation showed that, out of 900 particles initialized in the inner EE-slot region, 890 particles were collected at the vacuum outlet, corresponding to a 98.89% simulated collection ratio in Table 1. Overall, the combined flow-field patterns and the simulated collection ratio provided an evidence-based CFD indication of whether the selected chamber-only purge configuration could support vacuum-driven particle removal under the modeled conditions (Table 1).

Table 1. Result Particle Count Simulation

Particle Count Simulation					
Material	**Particle size**	**Input**	**Exit A(R+L)**	**Exit B**	**Exit A+B**
Aluminum	0.1 µm	100	88	11	99
	0.3 µm	100	86	13	99
	0.5 µm	100	84	15	99
Plastic	0.1 µm	100	86	13	99
	0.3 µm	100	86	13	99
	0.5 µm	100	85	14	99
Glass	0.1 µm	100	87	12	99
	0.3 µm	100	85	14	99
	0.5 µm	100	83	15	98
		900	770	120	890
		Efficiency = 98.89 %			

4. Data Collection

Data collection in this study focused on capturing maintenance-driven downtime characteristics associated with PM activities on platter-handling EE. Baseline data were obtained from PM logs, maintenance records, and routine production observations. Key variables included PM/cleaning frequency, downtime per event, recovery and buy-off duration, and recurring contamination symptoms observed on critical EE contact surfaces. These inputs were structured using fishbone diagram analysis to classify contributing factors across machine, method, material, and man, and to translate dominant downtime drivers into measurable design requirements and operating constraints for an in-machine ASC chamber. The resulting requirement set was then used to define SolidWorks Flow Simulation boundary conditions and evaluation metrics for simulation-based airflow assessment of the proposed concept.

5. Results and Discussion

The CFD results from SolidWorks Flow Simulation indicated that the air-jet purge combined with vacuum extraction generated an airflow field that was not uniformly effective across all critical surfaces. Flow visualization suggested low-velocity regions and localized recirculation near geometric corners and partially shielded areas, which could have increased the likelihood of particle trapping or re-circulation rather than direct transport toward the extraction path. Under this configuration, removal potential was sensitive to particle location relative to dominant flow streamlines, and longer residence was more likely in zones where the purge flow did not sufficiently sweep the surface. Across the investigated particle sizes, the simulated behavior remained consistent with transport governed by airflow structures: particles that followed streamlines could have persisted within vortical regions, whereas particles exposed to weak local sweeping effects could have remained near surfaces, increasing the potential for retention or re-deposition. From a process perspective, these CFD insights supported the design rationale for an embedded Auto Self-Cleaning concept using purge-and-extract; however, production validation remained necessary to quantify cleaning performance and downtime impact under manufacturing conditions.

5.1 Effective Downtime Reduction

The embedded ASC was expected to shift from an offline, labor- and handling-dependent workflow to a standardized in-machine cycle, fundamentally changing the downtime profile from variable and overrun-prone to short and predictable. Under the current PM plan (60 minutes/day), the offline ultrasonic routine typically expanded to 85 minutes per event, creating a consistent 25-minute unplanned overrun that disrupted daily scheduling at bottleneck operations, as shown in Figure 7. With the embedded purge-and-extract approach, downtime per cleaning event was projected to decrease from 85 minutes to 15 minutes, a 70-minute reduction, enabling the cleaning activity to fit within the intended PM window with substantially higher repeatability.

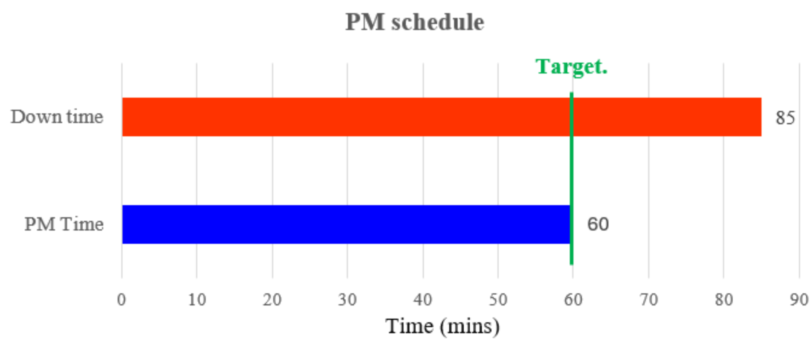


Figure 7. Preventive maintenance downtime schedule

At the system level, this reduction was expected to directly increase available production time and stabilize flow by reducing schedule drift and recovery uncertainty after maintenance. The more controlled, in-tool cleaning cycle also was expected to reduce operator-dependent variation linked to reinstallation and verification, which in turn was expected to lower the risk of post-maintenance alignment shift and improve consistency in tool return-to-run performance. If cleaning-event frequency remained unchanged, total cleaning-related downtime was projected to drop proportionally by 82.4% in Table 2. Further benefits were anticipated if embedded cleaning could be applied preventively to reduce the frequency of unplanned or reactive cleaning events.

Table 2. Expected after improvement downtime

No.	Cleaning Event Step	Before (min) (Offline Ultrasonic)	After (min) (Auto Self-Cleaning)
1	Stop Machine + Remove EE	5	0
2	Travel to cleaning room	10	0
3	Ultrasonic cleaning	30	0
4	Drying	15	0
5	Re-Assembly	5	0
6	Process buy off	15	0
7	Auto Self-Cleaning in machine	0	15
	Total downtime	85	15
	Improvement	Before-After	Reduction = 82.4 %

5.2 Discussion

The projected reduction in cleaning-induced downtime suggested that productivity loss was driven primarily by the conventional offline ultrasonic maintenance sequence and its recovery-related variability, rather than isolated equipment limits. Embedding an ASC function using an air-jet purge with controlled vacuum extraction was designed to directly address the fishbone-identified drivers by removing dependence on external cleaning and reducing requalification-related disruption. A CFD-informed chamber and nozzle configuration was used to stabilize evacuation airflow, lower re-deposition risk, and support more consistent cleaning behavior under manufacturing constraints. Overall, this work indicated that combining qualitative root-cause structuring with physics-based airflow evaluation was considered a practical route to in-machine cleaning solutions intended to improve availability while maintaining process stability in high-precision HDD assembly.

5.3 Integration Potential with AI, IoT and Smart Optimization

Although the proposed ASC concept primarily focuses on mechanical integration and CFD-based airflow optimization, its architecture establishes a scalable and data-driven contamination-control platform aligned with Industry 4.0 principles. Beyond static hardware improvement, the embedded chamber, purge configuration, and vacuum-assisted extraction system can evolve into an adaptive cleaning subsystem through IoT-enabled sensing, AI-based predictive strategies, and smart optimization frameworks.

First, real-time monitoring can be implemented by integrating pressure sensors, airflow sensors, and compact particle counters within the cleaning chamber. Continuous tracking of purge velocity, vacuum stability, and residual particle concentration would enable condition-based cleaning instead of fixed preventive maintenance (PM) intervals. This transition from time-based to performance-based maintenance directly supports TPM principles and enhances equipment availability and OEE transparency, particularly at bottleneck stations where downtime variability strongly affects line throughput (McKone et al. 2001; Swanson 2001; Achouch et al. 2022). Furthermore, CFD-identified low-velocity regions and recirculation zones may serve as feedback indicators for adaptive purge control, linking simulation insights with real-time operational data.

Second, predictive analytics may be employed to model contamination growth behavior across multiple cleaning cycles. Historical data such as cleaning frequency, downtime duration, particle-removal performance, alignment stability, and process drift indicators can be used to train machine-learning models capable of predicting optimal cleaning timing. Instead of executing cleaning at fixed daily intervals, predictive algorithms may estimate contamination thresholds and trigger cleaning only when necessary. This approach reduces unnecessary intervention, minimizes maintenance-induced variability, and strengthens process stability under high-precision assembly constraints. Such integration aligns with Industry 4.0 digital maintenance strategies (Achouch et al. 2022).

Third, future development may incorporate multi-objective optimization linking airflow parameters with manufacturing-level KPIs, including OEE, cycle-time impact, energy consumption, and process capability. Surrogate or reduced-order models derived from CFD results could accelerate design iteration and operational tuning. In a broader framework, a digital-twin representation of the ASC module may enable simulation-assisted adjustment of purge velocity and extraction balance under varying production conditions, transforming the ASC chamber from a fixed cleaning device into a semi-autonomous, self-optimizing subsystem.

Overall, the integration of Lean root-cause structuring, CFD-based airflow validation, IoT-enabled sensing, and AI-driven predictive control forms a cohesive smart-manufacturing framework. This layered architecture not only reduces cleaning-induced downtime but also enhances system responsiveness, quality robustness, and long-term manufacturing resilience at critical HDD assembly operations.

6. Conclusion

The in-machine ASC concept was projected to substantially reduce cleaning-induced downtime. Based on the step-level time breakdown, downtime per cleaning event was estimated to decrease from 85 minutes to 15 minutes, corresponding to a 70-minute reduction (82.4%). In addition to time savings, the approach is expected to reduce manual handling and operator-dependent recovery variability, thereby improving equipment availability (OEE) and process stability at bottleneck operations.

Beyond downtime reduction, the ASC concept establishes a scalable and data-driven contamination-control architecture for smart manufacturing integration. Future implementation incorporating IoT-enabled monitoring, AI-based predictive cleaning strategies, and digital-twin-assisted optimization may further enhance equipment availability, reduce maintenance variability, and strengthen data-driven Lean and TPM deployment in high-precision HDD assembly environments.

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