

Innovation & Transformation at Singapore Changi Airport and a Case Study on AI-enabled Line Maintenance Operations

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Abstract

Singapore's aviation sector is developing a connected approach to airport innovation in which digitalisation, artificial intelligence and automation are applied across the passenger journey, terminal operations, the airside and aircraft maintenance. Changi Airport Group (CAG), as the airport ecosystem orchestrator, provides the primary frame for this case study. Its transformation agenda responds to four imperatives: maintain best performance, maximise capacity, strengthen operational resilience and increase manpower productivity. The portfolio includes automated passenger processing, the New Clearance Concept, advanced data analytics, AI-enabled security screening, cleaning robots, video analytics for aircraft turnaround and safety, autonomous vehicles, robotics fleet management, sustainability initiatives, the Changi Living Lab and the long-term development of Terminal 5.

The paper uses SIA Engineering Company's (SIAEC) Line Maintenance operation as an applied case within this wider airport transformation. The Electronic Line Maintenance Integrated Technology Ecosystem (ELITE) connects planning, execution, documentation and operational control, while AI-enabled task-card validation, defect-resolution support and workforce optimisation address specific productivity and reliability constraints. The combined proposition is an intelligent aircraft turnaround: airport, airline, ground-handling and engineering partners working from timely operational data, assisted by governed AI and increasingly capable automation. Embedded AI and soft robotics extend this direction through human-centred tools at the point of work, subject to safety assurance, technical validation and accountable human decisions.

Executive proposition. Singapore's next aviation advantage will come from an airport ecosystem in which passenger, airside and engineering decisions are connected through trusted data, governed AI and human-centred automation.

1. Introduction

International hubs must accommodate growth while preserving safety, security, service quality and resilience. The traditional response of adding counters, vehicles or manpower is becoming less sustainable where land is constrained, labour is scarce and passenger expectations continue to rise. The challenge is therefore to make the airport system more productive and precise: information must travel faster, repetitive activity must be automated where appropriate, and people must be supported to concentrate on judgement, service recovery and safety-critical work.

Changi Airport illustrates the scale and interdependence of this challenge. In 2025 it handled 69.98 million passengers and connected Singapore with about 170 cities through some 100 airlines and more than 7,300 weekly flights. The airport community comprises more than 200 organisations and around 57,000 staff. CAG's role consequently extends beyond managing infrastructure. It orchestrates an ecosystem of airlines, ground handlers, government agencies, emergency services, service providers, tenants and commercial partners whose decisions converge in a shared operating environment.

Within that environment, the aircraft turnaround is a defining operational process. Passenger readiness, baggage, security, servicing, engineering clearance, ground movement and departure sequencing must be synchronised within a narrow window. Digitalisation and intelligent automation create value when they improve the performance of this entire chain. The airport-wide transformation is therefore the main narrative; SIAEC Line Maintenance provides a practical example of how a safety-critical partner can connect its own digital and AI capabilities to that common objective.

2. Changi Airport as ecosystem orchestrator

Changi's development has been guided by the principle that the airport is both national infrastructure and a service ecosystem. Safety and security form the foundation, followed by capacity, service and experience. Innovation must reinforce every layer: a passenger-facing improvement is not sustainable if it weakens throughput or resilience, while an operational technology does not reach its full value if it creates friction for passengers or frontline staff.

CAG's orchestrator role is especially important because no single organisation controls the complete passenger journey or aircraft turnaround. Common operating standards, trusted data, shared milestones and coordinated trials enable multiple partners to innovate without fragmenting the airport. This system perspective also establishes the bridge to maintenance: aircraft readiness is one of the critical conditions on which airport flow, stand utilisation and network punctuality depend.

3. Transformation imperatives and operating philosophy

Four imperatives shape Changi's transformation: maintaining best performance, maximising capacity, strengthening operational resilience and increasing manpower productivity. These priorities respond directly to persistent manpower shortages in activities such as ground handling and cleaning, tight peak-hour capacity at selected touchpoints, and changing expectations of a personalised, stress-free and positively surprising airport experience.

CAG treats digital and automation initiatives as operating-model change rather than equipment procurement. Technology readiness must be matched by process readiness and business readiness. A technically capable robot, analytic model or autonomous vehicle will not scale unless workflows, accountabilities, maintenance support, economics, training and exception handling are designed around it.

This approach places advanced data analytics at the centre of transformation. Operational data can expose queues, predict emerging constraints, identify unsafe behaviour and support coordinated interventions. Automation then acts on selected parts of the process, while people retain responsibility for ambiguous, customer-sensitive and safety-critical decisions. The intended outcome is not technology for its own sake, but a more consistent and adaptive airport.

The same philosophy governs collaboration with airport partners. CAG defines the common problem and operating environment, brings stakeholders into realistic trials, and scales solutions only when operational performance is repeatable. This creates a disciplined pathway from an idea to an airport capability and reduces the risk of isolated pilots that cannot be integrated or sustained.

4. Digital passenger journey and terminal automation

Passenger processing demonstrates how digitalisation can expand effective capacity without a proportional increase in physical counters. Fast and Seamless Travel (FAST) automates key touchpoints, and the New Clearance Concept advances automated immigration clearance. Together, these initiatives shift routine processing towards self-service and allow officers and service personnel to focus on exceptions and passengers who require assistance.

AI-enabled security screening adds a decision-support layer. The objective is to improve screening productivity and consistency while preserving the authority and accountability of trained security personnel. The operating design must address model performance, escalation, false alarms, human review and continuous monitoring, because a security innovation is credible only when it strengthens both throughput and assurance.

Robotics addresses labour-intensive terminal work. Changi has deployed approximately 60 floor-scrubbing and sweeping robots, reducing the equivalent workload of about 48 cleaners and generating reported annual savings of approximately S$900,000. AI-enabled spot cleaning uses operational signals to direct cleaning where it is needed, and a projected fleet of about 100 toilet-cleaning robots is intended to reduce repetitive work equivalent to approximately 39 cleaners. These deployments show how sensing, task allocation and robotics can be combined rather than treated as separate technologies.

Automation also supports the quality of the Changi experience. By reducing queues and routine workload, the airport can protect the human interactions that matter most: assistance, reassurance and disruption recovery. Digitalisation therefore complements Changi's service philosophy and physical experience, including its emphasis on nature, tranquillity and memorable passenger spaces.

5. Airside innovation and the intelligent turnaround

At the airside, CAG's vision is to increase operational precision and reduce manpower dependency in aircraft turnaround. The portfolio includes automated passenger loading bridges, one-person aircraft pushback, digital tools for ramp supervision, autonomous vehicle tractors and baggage-handling robots. Each addresses a different source of manual coordination, repetitive movement or variability around the aircraft.

Video analytics provides a common sensing layer. Turnaround analytics can observe operational milestones and highlight deviation from plan; safety analytics can identify selected unsafe conditions or behaviours for intervention and learning. Used well, video analytics changes supervision from retrospective investigation to earlier, evidence-based response. It must nevertheless be bounded by clear purpose, data governance, performance validation and human review.

Autonomous vehicles and robotic ground-support equipment require more than navigation technology. Their deployment depends on geofenced operating rules, interaction with people and conventional vehicles, communications coverage, charging, fleet management, recovery from degraded modes and safe behaviour

near aircraft. Robotics fleet management is therefore a strategic capability: it coordinates tasks and availability across multiple machines while maintaining visibility for human controllers.

Line Maintenance is integral to this airside system. A turnaround may be passenger-ready and baggage-ready yet still be constrained by an unresolved defect, an unavailable engineer, incomplete documentation or delayed certification. Conversely, engineering teams benefit when stand status, vehicle movement, weather, baggage progress and departure risk are visible. The maintenance case presented later in this paper demonstrates how SIAEC's operational data and AI tools can connect with the wider airport objective.

6. Innovation through the Changi Living Lab

Many airport problems have no off-the-shelf solution. Technologies developed for factories, warehouses or public roads must be adapted to live terminal and airside conditions, including dense stakeholder interaction, variable demand, aircraft-protection requirements, rain, heat and lightning. CAG's Living Lab allows the airport and its partners to move from buyer-vendor relationships towards co-development.

A Living Lab trial should test an operational hypothesis, not only a technical feature. Relevant measures include safety events, task completion, throughput, intervention frequency, manpower effort, passenger or worker acceptance, system availability and recovery time. Trials also reveal process changes, infrastructure interfaces and maintenance burdens that may not be visible in a controlled demonstration.

The sandbox model is particularly relevant to AI and robotics. Models need representative operational data and monitoring for drift; autonomous equipment needs progressively more demanding scenarios; and human-machine procedures need rehearsal. Defined trial boundaries make experimentation faster while protecting live operations. Evidence from the sandbox then informs procurement, safety assurance and scaling decisions.

CAG's ability to convene airport stakeholders is a scaling advantage. A solution can be assessed not only by the team that operates it, but also by the airlines, handlers, engineering organisations, emergency services and regulators affected by it. This collaborative validation is essential for technologies that cross organisational boundaries during an aircraft turnaround.

7. Sustainability and operational resilience

Changi's innovation agenda is inseparable from sustainability. Its principal pillars are emissions reduction, waste management, water conservation and climate resilience. CAG directly controls emissions from its own assets and purchased electricity, while it influences a much larger airport-community footprint through infrastructure, standards and partnerships. This makes ecosystem coordination as important for decarbonisation as it is for operations.

Energy efficiency is pursued through regular upgrades of chillers and air-handling systems, progressive conversion of terminal and airfield lighting to efficient technologies, and intelligent controls that optimise system settings. A 38 MW rooftop solar system has been installed across terminal buildings. Beyond CAG's own facilities, the airport works with partners on ground-support-equipment electrification and the adoption of cleaner energy and fuels.

The airport has stated a target to reduce Scope 1 and 2 emissions by 20% by 2030 and a longer-term aspiration of net zero by 2050. Electrification and clean-fuel adoption can reduce emissions but also create new operational dependencies: charging capacity, energy scheduling, battery condition, asset availability and recovery arrangements must be integrated into daily control. Digital platforms and analytics are therefore enablers of both sustainability and reliability.

Climate resilience is an operating requirement. Infrastructure and work practices must remain safe under heavy rain, heat and lightning, while digital systems must remain available during disruption. The broader

lesson is that intelligent automation should be evaluated in adverse conditions, not only in ideal trials. Robustness, maintainability and graceful degradation are core design criteria for the future airport.

8. Terminal 5 and the next operating horizon

Terminal 5, planned for operation in the mid-2030s, is expected to add capacity for about 50 million passengers per year. Its significance is not simply physical scale. It offers the opportunity to embed automation, robotics, data-driven operations, sustainability and resilience into the operating concept from the outset rather than retrofit them after processes have stabilised.

The future terminal should be designed around integrated operations. A common operational picture can connect passenger flows, security, baggage, stands, vehicles, weather, engineering readiness and disruption response. Digital twins, predictive analytics and event-driven coordination can help teams anticipate constraints and evaluate recovery options before performance is lost.

Terminal 5 also raises the importance of interoperability. Technology choices must support shared data definitions, secure interfaces and modular evolution over several decades. Airport systems, airline systems and partner platforms will change at different speeds; the architecture must allow innovation without creating dependencies that are unsafe or uneconomic to replace.

The Line Maintenance case study is relevant to this horizon because engineering readiness must become a first-class component of integrated airport operations. SIAEC's experience shows how planning, mobile execution, AI-assisted assurance and operational control can be connected today, providing practical lessons for the future ecosystem.

Table 1 - Changi transformation portfolio and operating value

Domain	Representative capability	Operating value
Passenger journey	FAST and New Clearance Concept	Higher effective capacity and a more seamless journey
Terminal operations	Advanced analytics, AI security screening and cleaning robots	Productivity, consistency and earlier intervention
Aircraft turnaround	Automated loading bridges, one-person pushback and ramp tools	Greater precision and lower coordination burden
Airside mobility	Autonomous tractors, baggage robots and fleet management	Reduced repetitive movement and scalable automation
Operational awareness	Turnaround and safety video analytics	Earlier detection of delay and safety risk
Innovation system	Changi Living Lab and co-development	Evidence-based adaptation and scaling
Future airport	Terminal 5, sustainability and integrated operations	Capacity, resilience and long-term competitiveness

9. Line Maintenance case study: AI-enabled turnaround support

Line Maintenance is the engineering counterpart to ground handling. It ensures that an aircraft is safe, serviceable and ready for release within the turnaround window. SIAEC's Electronic Line Maintenance Integrated Technology Ecosystem (ELITE) links the Joint Planning Platform (JPP), Electronic Documents and Capacity Optimizer (eDCO), the Enhanced Operations Control Centre (EOCC) and SmartMX. The value lies in the operating chain created by these systems: plan the work, execute with live status, assure records

and compliance, and control exceptions from a shared picture. The ecosystem reflects SIAEC's wider objective of using AI and digitalisation to relieve capacity, talent, manual-effort and compliance constraints in a labour-intensive MRO business. It also shifts the transformation emphasis from digitising isolated forms to connecting operational decisions end to end.

9.1 Plan: JPP and optimized work allocation

JPP supplies the planned-work context, while the Workforce Optimisation Engine considers roster availability, flight schedules, bay locations and task windows. Recommended assignments and sequences support pre-day and day-of-operations planning. Integration with EOCC's work-allocation capability and SmartMX allows the plan to become an operational workflow rather than remain a static schedule. The solver must respect operational constraints rather than optimise an abstract average. Skill and authorisation, shift and rest rules, aircraft type, task precedence, travel time and uncertainty all affect whether a recommendation is usable at the ramp.

The reported result for Line Maintenance manpower assignment is an 85% reduction in scheduling time, together with overtime savings. The larger benefit is adaptability: when aircraft, manpower, stand or weather conditions change, planners can evaluate revised allocations more quickly and protect readiness-critical work. Supervisors can compare recommendations with local knowledge, accept or adjust assignments, and retain authority over the final deployment. This preserves operational flexibility while making the planning logic more consistent and auditable.

9.2 Execute: SmartMX and real-time readiness milestones

SmartMX provides mobile execution and live maintenance-readiness milestones. Progress becomes visible as operational data rather than remaining in local conversations or paper updates. A late task, emerging defect or certification risk can therefore be recognised as a turnaround deviation and escalated earlier. Capturing these events consistently also improves post-operation learning. Planned and actual times, interruptions and completion evidence can be analysed to refine workload assumptions, identify recurring bottlenecks and improve the next planning cycle.

This visibility creates the interface with the airport. Engineering readiness can be considered alongside stand activity, boarding, baggage and departure sequencing. It also establishes the data foundation for future embedded AI, because assistance at the point of work depends on current task, aircraft and operational context. A common milestone vocabulary is important: airport and engineering teams need to interpret readiness states consistently, while sensitive technical detail remains protected within the maintenance authority and access-control framework.

9.3 Assure: eDCO, task-card validation and AI vetting

eDCO supports electronic-document workflows and embeds AI in selected assurance processes. The AI-Powered Task Card Validator reads a signed task-card PDF, extracts required information, checks compliance parameters and flags discrepancies for supervisor review before filing. Reported validation time has fallen by 98%, from five minutes to seven seconds per card. At approximately 500 cards a day, this removes about 41 hours of manual validation effort while accelerating feedback and strengthening audit readiness. The tool has been in use since 2025, with scaling across Line Maintenance, Technical Services and Planning, and Base Maintenance. Its design converts a repetitive administrative check into exception-based supervision: the system performs the first pass, while the supervisor concentrates on discrepancies and accountable acceptance.

AI-assisted vetting can also support the commercial completeness of maintenance records. Relevant documents are analysed to identify billable activities and supporting evidence, with planners reviewing the recommendation. This illustrates a useful pattern for safety-critical operations: AI performs high-volume reading and consistency checks, while an authorised person confirms the consequential decision. The

quality of the result depends on traceable source documents, clear extraction rules and a visible link between evidence and recommendation. Low-confidence or incomplete cases should be routed to manual review rather than forced through an automated outcome.

9.4 Control: EOCC Situational Awareness and Response

EOCC Situational Awareness and Response (SAR) provides the command-centre layer. It combines schedule context, SmartMX readiness milestones, JPP task status, aircraft alerts and OEM reliability information. AI-assisted severity filtering, event-driven updates, and visual and audio alerts help operations teams focus on deviations that require attention. The operating picture is event-driven. Rather than asking controllers to poll multiple applications, it highlights changes in flight status, task progress, readiness risk and alert severity. The controller can then assess operational impact and coordinate engineering, parts, manpower and recovery actions.

A unified operating picture supports earlier issue detection and coordinated action across approximately 50 users per shift. Engineer Assist complements this control layer by retrieving successful historical responses to similar defects. Reported outcomes include a 75% reduction in Technical Services Engineer assessment time, about 720 engineering hours saved annually, and an expected improvement in right-first-time troubleshooting. These measures demonstrate decision support rather than autonomous engineering judgement. For around 720 operational defects a year, the use case is expected to avoid rework in approximately 72 cases and save about 576 combined Licensed Aircraft Engineer and technician hours annually. These estimates should continue to be monitored against operational baselines as usage expands.

9.5 Case-study outcome

ELITE turns four operational verbs into a connected Line Maintenance system: JPP and optimisation plan; SmartMX reports execution; eDCO assures documentation and compliance; and EOCC-SAR coordinates control and response. The components are valuable individually, but their greater contribution is the shared flow of context across planning, frontline work and the operations centre. A trusted data backbone is essential. Enterprise applications and common AI, optimisation and agent-service layers can provide reusable components and guardrails, while named data owners address gaps, duplicates and inconsistent coding that would otherwise undermine operational recommendations.

The case remains human-in-the-loop. AI can retrieve information, classify events, recommend actions, flag inconsistencies and optimise allocation. Licensed engineers and authorised supervisors remain responsible for technical decisions, certification, operational trade-offs and escalation. This division of labour is central to safe adoption and to confidence among regulators, customers and the workforce. Recommendations should show the supporting evidence and confidence needed for review. Permissions, escalation paths and audit records must be explicit, and consequential actions must support safe interruption or reversal wherever technically possible.

10. Embedded AI and soft robotics

Within the Line Maintenance context, machine sensing, machine intelligence and mechatronic assistance at the point of work further enhance operations with collaborative robotics. It extends digitalisation beyond the control room: the engineer receives relevant information and physical assistance in the operational environment where the task is performed.

Embedded AI can provide contextual retrieval of approved technical information, task-card checks, defect diagnostics, recommended inspections, predictive cues, computer-vision support and disruption sensing. Its purpose is to reduce search, improve consistency and surface risk earlier. It should not be framed as autonomous certification; the approved maintenance data, authorisation framework and accountable engineering decision remain controlling. Retrieval and recommendations must be grounded in controlled

technical sources. Version status, applicability and provenance should be visible to the engineer, and offline or degraded-connectivity operation should be considered for ramp conditions. Model updates should be validated before release and monitored for unexpected behaviour after deployment.

Soft robotics adds compliant physical assistance where work is repetitive, ergonomically demanding, constrained by aircraft geometry or sensitive to contact forces. Potential applications include adaptable inspection tools, sensor or camera positioning, lightweight tooling assistance and constrained-area handling. CAG's experience with baggage robots, cleaning robots and autonomous vehicles provides an adjacent airport test environment, but every aircraft-maintenance application requires its own safety case and aircraft-protection controls. Soft-robotic devices should be assessed as aviation tools, including calibration, foreign-object-debris control, cleaning, storage, battery safety and damage-tolerance requirements. Contact forces and failure modes near aircraft structure require particular attention. The system should default to a safe state and allow the operator to disengage it immediately.

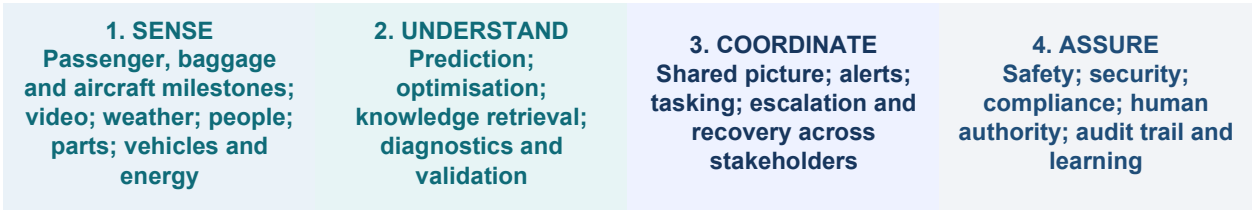
The strongest model is human-centred augmentation. Technology should reduce low-value movement and manual checking, improve access to knowledge and help personnel perform difficult tasks more safely. Progression from prototype to deployment should depend on technical reliability, maintainability, cybersecurity, workforce acceptance and measurable operational benefit under live conditions. Deployment can progress through observation, advisory assistance, supervised execution and only then bounded automation. Each step should have measurable acceptance criteria, defined training and a clear maintenance owner for the technology itself. This staged approach allows capability to grow without moving faster than the safety evidence or frontline confidence.

11. Integrated airport-MRO operating model

The combined airport and Line Maintenance experience supports an integrated model for aircraft turnaround. Airport video, passenger and baggage milestones, aircraft alerts, task status, weather, people, parts and vehicle telemetry establish the operational facts. Analytics, optimisation and knowledge retrieval interpret those facts. Shared workflows coordinate the response, while assurance mechanisms bound every action.

The model has four layers. Sensing creates a timely and trusted view of the operation. Intelligence predicts, diagnoses, validates or recommends. Coordination aligns people, systems and assets around a shared plan. Assurance provides safety, security, compliance, human authority, auditability and learning. The layers are deliberately organisation-neutral so that airport, airline, handler and MRO capabilities can connect without erasing their distinct accountabilities.

Figure 1 - Integrated airport-MRO operating model



CAG provides the ecosystem context and common operating environment; SIAEC's ELITE provides the Line Maintenance implementation. Video analytics and operational milestones support sensing, AI and optimisation support intelligence, EOCC-style workflows support coordination, and eDCO-style validation illustrates assurance. The concept is a federated operating model, not a single monolithic system.

Implementation should be progressive. Early phases should establish reliable digital milestones and interfaces. Later phases can add predictive models, increasingly automated recommendations, autonomous logistics and soft-robotic assistance where evidence supports deployment. Throughout, degraded modes and manual recovery must remain part of the design.

12. People capability and workforce transformation

Automation changes the content of airport work rather than removing the need for skilled aviation professionals. Terminal staff, ground handlers, controllers, engineers and technicians increasingly supervise machines, interpret analytics, manage exceptions and coordinate across digital workflows. The workforce proposition is to remove repetitive effort and improve decision quality while preserving human service and safety judgement.

CAG's readiness model highlights why adoption cannot be treated as a final training activity. Processes, roles, industrial arrangements, operating procedures and performance measures must evolve with the technology. Frontline users should participate in trial design because they understand edge cases and practical constraints that are rarely captured in a technical specification.

SIAEC's Line Maintenance experience adds the need for AI literacy in a regulated setting. Users must understand the source and limits of a recommendation, know when to challenge it, and record the accountable decision. Digital tasking and mobile execution also require reliable devices, connectivity and practical job design at the aircraft.

Across the airport community, shared language and coordinated human-machine procedures are essential. A ground handler, airport controller and engineer may each see a different part of the same disruption. Joint exercises and common escalation patterns help those perspectives converge quickly, particularly when automated systems are operating in the same physical space.

13. From experimentation to ecosystem-scale delivery

CAG's transformation logic combines technology, process and business readiness. Strategic initiatives such as integrated operations, autonomous airside systems and major terminal automation require coordinated investment and multi-stakeholder governance. Smaller workflow and analytics improvements can move faster within defined guardrails, generating evidence and operational learning.

The Living Lab provides the bridge between the two. A bounded experiment can establish technical feasibility, but scale requires an operating owner, support model, cybersecurity controls, workforce acceptance, sustainable economics and measurable service or productivity value. The same gate should apply whether the innovation originates with CAG, an airport partner, a technology company or a frontline team.

SIAEC's portfolio illustrates how local improvements can connect to a strategic platform. Task-card validation, Engineer Assist and workforce optimisation solve bounded problems, while ELITE and EOCC-SAR provide the data and workflow backbone through which those capabilities can be governed and reused. This relationship between platform and use case is directly relevant to airport-wide innovation.

Ecosystem-scale delivery therefore avoids a false choice between central coordination and local experimentation. CAG can establish shared outcomes, interfaces and assurance expectations, while partners develop capabilities in their own operational domains. Successful solutions are then integrated where cross-stakeholder value justifies the effort.

14. Roadmap for intelligent aircraft turnaround

A practical roadmap begins with a shared value-stream map across airport, airline, ground handler and MRO stakeholders. High-frequency delays, manual handoffs, safety exposures, resource constraints and weather disruptions should be measured against agreed baselines. This creates a common problem definition before technology choices are made.

The next stages establish digital milestones and data ownership, introduce AI-assisted decisions, automate selected physical tasks and finally integrate cross-stakeholder workflows. Candidate measures include turnaround variability, passenger and baggage milestone adherence, defect-assessment time, rework, planning effort, manpower utilisation, safety events, energy use and customer impact.

Table 2 - Proposed implementation roadmap

Phase	Focus	Representative deliverables	Scaling gate
1	Diagnose	Shared turnaround map; baseline measures; priority constraints	Clear ownership and measured problem
2	Digitalise	Common milestones; mobile updates; data ownership and interfaces	Reliable data and workflow adoption
3	Assist	Prediction; task-card checks; defect support; scheduling and alerts	Safety, productivity and user evidence
4	Automate	Autonomous logistics; computer vision and validated robotic assistance	Safety case and operational reliability
5	Integrate	Cross-stakeholder operating picture; governance and continuous learning	Repeatable ecosystem performance

Evidence before scale is the governing principle. A prototype becomes an operating capability only when it is safe, reliable, maintainable, secure, accepted by the workforce and effective under realistic airport

conditions. Scaling decisions should also consider interoperability and whether benefits are realised across the ecosystem rather than shifted from one participant to another.

15. Discussion

Changi's innovation portfolio shows that airport transformation is a system endeavour. Passenger automation, security AI, cleaning robots, airside analytics, autonomous vehicles, sustainability and Terminal 5 planning address different operating problems, but they share the same need for trusted data, redesigned processes, human-machine coordination and disciplined scaling.

The Line Maintenance case gives this airport narrative operational depth at the aircraft. ELITE demonstrates how a partner organisation can connect planning, mobile execution, documentation and control, while targeted AI and optimisation remove specific bottlenecks. It is an elaboration of the airport model, not a separate technology programme.

Three lessons emerge. First, integrate around the operational outcome rather than the technology category. Second, distinguish sensing, decision support, coordination and consequential action so that governance is clear. Third, use the airport as a collaborative validation environment, because the most valuable innovations often cross organisational and physical boundaries.

The next frontier is increasingly embodied and contextual intelligence. Embedded AI and soft robotics can bring knowledge, sensing and assistance closer to frontline work, but aviation will demand stronger evidence than a laboratory demonstration. Singapore's advantage lies in combining an orchestrating airport operator, capable industry partners, a realistic Living Lab and a workforce accustomed to high standards of safety and service.

16. Conclusion

Changi Airport's transformation is driven by the need to sustain hub competitiveness while addressing manpower, capacity, passenger-experience, sustainability and resilience challenges. CAG's airport-wide portfolio demonstrates how digitalisation, AI and automation can augment people across the terminal and airside, and how the Living Lab can turn novel technology into an operational capability.

SIAEC's Line Maintenance case shows how that ambition reaches the aircraft. ELITE connects plan, execute, assure and control; AI-enabled validation and defect support reduce manual effort; optimisation improves resource allocation; and embedded AI and soft robotics define a credible human-centred direction for point-of-work innovation.

Together, the airport and maintenance perspectives support a Singapore model of intelligent turnaround built on sensing, intelligence, coordination and assurance. The model preserves organisational accountability while enabling a shared operating picture and faster, more reliable decisions. With evidence-based scaling and trusted human-machine operations, it can strengthen capacity, productivity, resilience and the passenger experience at ecosystem scale.

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Appendix A - Innovation portfolio at a glance

- Passenger flow: FAST and the New Clearance Concept automate routine passenger-processing touchpoints and protect capacity for assisted service.
- Terminal operations: advanced analytics, AI-enabled security screening and cleaning robots improve productivity, consistency and responsiveness.
- Airside operations: automated passenger loading bridges, one-person pushback, autonomous tractors, baggage robots and video analytics support a more precise turnaround.
- Innovation system: the Changi Living Lab enables co-development, operational trials and evidence-based scaling where off-the-shelf solutions are insufficient.
- Sustainability and resilience: energy efficiency, a 38 MW rooftop solar system, electrification, cleaner fuels and climate adaptation strengthen long-term airport performance.
- Line Maintenance case: ELITE connects planning, mobile execution, AI-enabled assurance and situational control around aircraft readiness.
- Future horizon: Terminal 5, integrated operations, embedded AI and soft robotics extend the human-centred transformation of the airport ecosystem.