SMART RAMP

The future ConOps of the aircraft turnaround

SMART RAMP PROGRAM

FUTURE TRAVEL EXPERIENCE

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THE FUTURE CONOPS OF THE AIRCRAFT TURNAROUND

FOREWORD

The aircraft turnaround is one of the most demanding choreographies in modern aviation. In the space of thirty to sixty minutes, an aircraft is met, emptied, serviced, reloaded, boarded and sent on its way through the combined effort of airlines, airports, ground handlers, fuel suppliers and many others. It is where schedules are kept or lost, where billions in ground-damage and delay costs accumulate, and where our colleagues on the ramp work hard, often in difficult conditions. It deserves our full attention.

This whitepaper sets out a shared Concept of Operations for that turnaround, a vision of a ramp that is healthier for the people who work it, more predictable for the passengers who depend on it, and more efficient and sustainable for the industry as a whole. It is the culmination of the Smart Ramp program, now in its second year, together with four days of intensive workshops with some of the world's leading airports and airlines.

The Smart Ramp program was designed and created by nlmtd in close cooperation with the Future Travel Experience and its former CEO, Daniel Coleman. What sets this work apart is that it has not been written for the industry from the outside, but with the industry from the inside out. A recurring lesson of these two years is that the technology is largely ready; the real work is organisational, regulatory and cultural — and that work can only be done together, through alignment, integration and shared direction.

My sincere thanks go to every airport, airline, partner and individual who chose to step out of their day-to-day and help shape this future. Your openness, candour and ambition to change the industry from within are what made this document possible.

Finally, this is an invitation. If you are an airport, an airline, a ground handler, a regulator or a technology provider, I encourage you to use this whitepaper to your advantage — and to reach out to us. The conversations that matter most are the ones that must begin now, and the more of us at the table, the faster we can bring the industry forward together.

With warm regards,

Manuel van Lijf
Director of Aviation, nlmtd
Amsterdam, The Netherlands

GLOSSARY

This glossary defines key terms used throughout the whitepaper, combining industry-standard abbreviations with Smart Ramp specific concepts.

TERM	DEFINITION
A-CDM	Airport Collaborative Decision Making — framework for sharing real-time operational data between airport stakeholders.
AHM 908	IATA Airport Handling Manual 908 — data exchange standard for ground operations.
AIBT	Actual In-Block Time — timestamp when the aircraft is fully chocked at the stand.
AIDX	Aviation Information Data Exchange — IATA XML messaging standard for flight data.
AODB	Airport Operational Database — central system holding flight, resource and movement data.
ATC	Air Traffic Control.
Auto-PBB / Auto-SEGS	Autonomously operated Passenger Boarding Bridge / Stand Entry Guidance System.
Biometric Boarding	Use of facial recognition or other biometrics to identify passengers at the gate.
ConOps	Concept of Operations — a high-level description of how a system or operation will work in the future.
DCS	Departure Control System — airline IT system that handles check-in, boarding and load control.
ELIR	Electronic Load Instruction and Reconciliation — IATA digital standard replacing paper LIRs.
EOTI / SETO	Engine-Out Taxi-In / Single Engine Taxi-Out — fuel-saving taxi procedures.
FOD	Foreign Object Debris — any object that does not belong on the apron and can damage aircraft.
FSZ	Fuelling Safety Zone — exclusion area around fuelling operations.
GHA	Ground Handling Agent.
GPU / PCA	Ground Power Unit / Pre-Conditioned Air — services supplied to the parked aircraft.
GSE	Ground Support Equipment — vehicles and equipment used to service aircraft on the ramp.
GVI	General Visual Inspection — visual inspection of the aircraft exterior.
HOT	Hold-Over Time — the time anti-icing fluid remains effective after application.
IATA	International Air Transport Association.

GLOSSARY

This glossary defines key terms used throughout the whitepaper, combining industry-standard abbreviations with Smart Ramp specific concepts.

TERM	DEFINITION
IGOM	IATA Ground Operations Manual — the global procedural standard for ramp operations.
ITP	Into-Plane fuelling — physical transfer of fuel from a refueller/hydrant to the aircraft.
LIR	Loading Instruction Report — instructions to the loading team on compartment distribution.
LoRaWAN	Long Range Wide Area Network — low-power IoT connectivity used in airport sensor toolkits.
NOTOC	Notification to Captain — communication summarising special loads and dangerous goods on board.
OBT	Off-Block Time — actual time the aircraft pushes back from the stand.
OTP	On-Time Performance.
PBB	Passenger Boarding Bridge — the jet bridge connecting terminal to aircraft.
PoT	Proof of Technology.
PRM	Persons with Reduced Mobility.
SAF	Sustainable Aviation Fuel.
TaxiBot / Wheel-Tug / e-Taxi	Systems enabling engine-off taxiing of aircraft.
TRL	Technology Readiness Level — 1 (basic principles) to 9 (proven in operations).
ULD	Unit Load Device — container or pallet for transporting baggage/cargo on aircraft.
VDGS	Visual Docking Guidance System — guides the pilot to the parking position.
X565	IATA standard automating weight-and-balance data exchange.

EXECUTIVE SUMMARY

SMART RAMP CONOPS: **THE FUTURE OF AIRCRAFT TURNAROUND**

The aircraft turnaround sits at the operational and economic heart of aviation. In a typical 30–60 minute window, an aircraft is disembarked, serviced, reloaded, boarded and dispatched through a complex choreography involving airlines, airport operators, ground handlers, fuel suppliers, caterers and air navigation service providers, most of it still executed manually under significant time pressure.

This whitepaper presents **the Smart Ramp consortium's complete Concept of Operations (ConOps) for the future aircraft turnaround**, fifteen years out. It is the consolidated result of the Smart Ramp 2025 program, two co-design workshops, and ongoing input from nine leading airlines, airport authorities and airports across Europe, North America and Asia-Pacific.

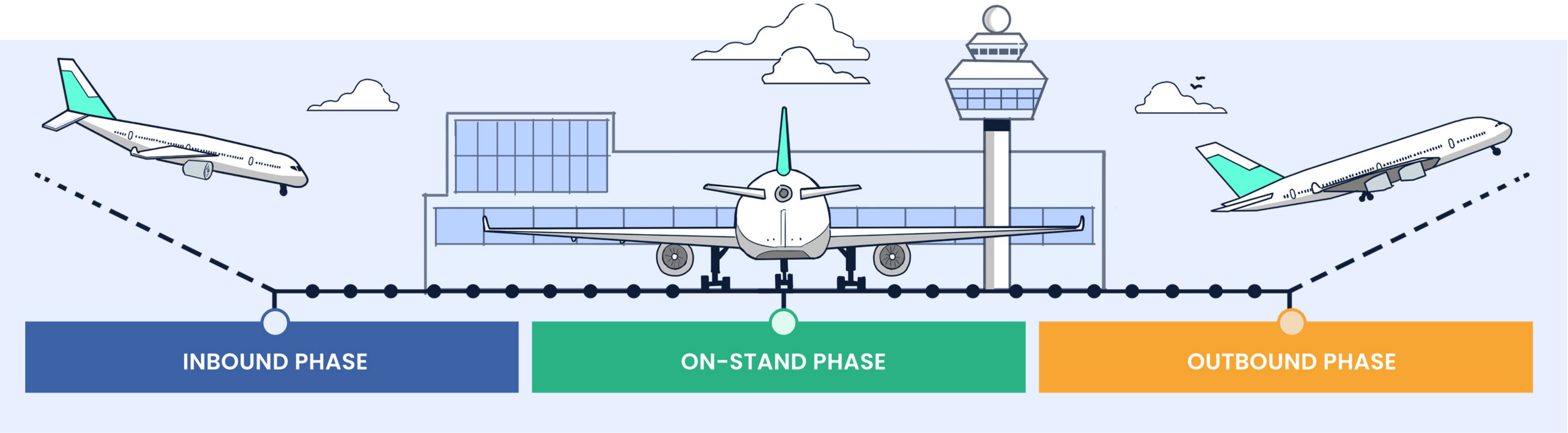
It covers all eighteen IATA IGOM-aligned process steps grouped into Inbound (steps 1–9), On-Stand servicing (steps 10–13) and Outbound (steps 14–18).

WHAT THIS DOCUMENT DOES

Diagnoses the current state of all 18 process steps using a People–Process–Technology framework, identifying six recurring thematic challenges.

Articulates the future ConOps through six paradigm shifts:

- **A remote command centre**
- **A new data and connectivity stack**
- **Autonomous robotics and vehicles**
- **The elimination or absorption of several manual steps**
- **A digital twin and orchestration layer***
- **Transformation of ramp roles**



Maps each of the 18 steps to a reimagined **future state and to the real-world vendor landscape**, with TRL estimates and Smart Ramp project anchors.

Sets the path forward for Smart Ramp 2026 and beyond, consortium expansion, scaling of proven pilots, IATA dialogue on IGOM updates, and operationalisation of the ConOps into procurement standards

**a digital twin (live operational model) and an orchestration layer (coordinating decisions and workflows)*

EXECUTIVE SUMMARY

SMART RAMP CONOPS: **THE FUTURE OF AIRCRAFT TURNAROUND**

Technology is no longer the constraint

Across all 18 process steps, mature solutions exist at TRL 7–9 in the categories where ramp operations bleed the most time and money. The bottlenecks are organisational — certification, integration with legacy systems, workforce adoption, regulatory alignment.

Software has outrun hardware.

Digital standards (IATA X565, ELIR, NOTOC) [8,9], AI turnaround timestamping, biometric pass-through and engine-out taxi software offer near-term, high-confidence gains and ship 12–18 months faster than equivalent GSE projects.

Two steps remain underserved by innovation

Toilet & Water Servicing (step 13) and Closing Doors & Predeparture (step 16). Both are candidates for focused Smart Ramp 2026 pilots.

The business case is far larger than headcount reduction.

Operational resilience (preventing knock-on delays at ~$100 per minute), safety risk reduction (~$10B/year in industry ground damage) [4], and sustainability (fuel and glycol savings) collectively dwarf direct labour savings. Framing automation as workforce augmentation, not replacement, has been the single biggest adoption lever in the 2025 program. Demographic changes also require a drastic rethinking of the use of manual labour.

Standards and interoperability are the multiplier

Up to 80% of innovation project time is spent on custom integrations. Adoption of IATA AHM 908, AIDX, X565, ELIR and a shared FOD library is the pre-condition for everything else to scale.

The Smart Ramp future is not **about replacing people** with machines. It is about elevating people from manual execution to strategic supervision, while creating an operation that is **safer, faster, more resilient and dramatically more sustainable**. The technology is ready.

SMART RAMP CONSORTIUM – WORKSHOP VISION STATEMENT

1 BACKGROUND AND CONTEXT

1. BACKGROUND AND CONTEXT

1.1 An industry under pressure

Global aviation is entering a period of major growth.

12 billion by 2030 +

ICAO expects over 12 billion travellers by 2030 [2]

18.8 billion by 2045 +

ACI forecasts passenger numbers will nearly double by 2045 to 18.8 billion [1]

4.9% growth by 2026 +

IATA projects 4.9% year-on-year growth in revenue passenger kilometres for 2026 [3]

This places heavy pressure on airport operations, particularly the ramp, where the aircraft turnaround remains

- **Labour-intensive**
- **Manually coordinated and fragmented**
- **and where staff work in ultra-fine-particle-polluted air.**

Inefficiencies have major financial consequences

$10 billion by 2035 −

IATA estimates aircraft ground damage costs the industry approximately $5 billion annually today and could double to nearly $10 billion per year by 2035 unless preventive action is taken [4].

IATA's IDX data identifies slips, trips, falls and impacts as the most common ground-handling injuries, with falls from height the most severe [5].

$85 billion by 2033 +

The global airport automation market is forecast to grow from approximately $55 billion in 2025 to over $85 billion by 2033 (5.6% CAGR) [6], underscoring the sector's shift toward greater technological support.

The pressure intensifies as the turnaround moves from inbound through on-stand servicing into outbound. Industry timing studies attribute the majority of avoidable turnaround delays:

- **To fuelling and cargo loading (resource arbitration)**
- **Passenger boarding (procedural variability)**
- **De-icing (weather-driven)**

Also the steps with the most active 2024–2026 innovation funnel.

1.2 The innovation paradox:
Many solutions, no shared vision

A remarkable wave of innovation is sweeping through aviation ground handling — autonomous FOD detection, remotely operated PBBs, AI-powered turnaround monitoring, robotic baggage loaders, exoskeletons, autonomous ground vehicles, biometric boarding, electric refuellers, engine-off taxi systems. Yet despite this ferment, the industry faces a paradox: individual innovations abound but no unified view of the future ramp exists. Airlines, airport operators, ground handlers and technology providers each pursue separate agendas, leading to incompatible investments, organisational inertia, prioritisation difficulty and collaboration barriers.

The Smart Ramp Global Benchmark Research done by nlmtd, covering inbound and on-stand/outbound, confirms that the primary barriers to adoption are now organisational and technical — certification, safety governance, integration with legacy systems, workforce adoption, and operating-model alignment. The technology is increasingly ready; it is the industry's collective ability to adopt, integrate and scale that lags behind.

1. BACKGROUND AND CONTEXT

1.3 The Smart Ramp program:
A collaborative response

Smart Ramp is an open innovation program co-founded by nlmtd and the Future Travel Experience that brings together leading airport operators and airlines to collaboratively **design, test and accelerate** the future of the aircraft turnaround.

In 2025, the program facilitated 19 innovation projects across 6 founding partners, 8 airport operators, 6 airlines and 10 technology suppliers; 15 projects were completed by early 2026 with the remainder in advanced execution. The cumulative output includes a shared FOD library, a regulatory best-practice framework and the People & Culture guidance underpinning this whitepaper.

The future vision documented here is the direct product of four days of co-design workshops with industry partners (Workshop 1 — inbound; Workshop 2 — on-stand and outbound) and ongoing consultation. The participating organisations represent a deliberately diverse cross-section of the global aviation ecosystem:

Organisation	Type	Region
ANA (All Nippon Airways)	Airline	**Asia-Pacific (Japan)**
IAG (International Airlines Group)	Airline Group	**Europe (UK, Spain, Ireland)**
KLM Royal Dutch Airlines	Airline	**Europe (Netherlands)**
Lufthansa	Airline	**Europe (Germany)**
Miami International Airport	Airport operators	**North America (USA)**
Munich Airport	Airport operators	**Europe (Germany)**
MWAA (Metropolitan Washington Air-ports Authority)	Airport Authority	**North America (USA)**
Schiphol Airport	Airport operators	**Europe (Netherlands)**
Southwest Airlines	Airline	**North America (USA)**

The program ambition is to create a future-ready, smart ramp ecosystem that sets new standards in efficiency, safety and sustainability — healthier and safer roles for employees, a predictable service that functions like clockwork, and an automated, partially autonomous operation that minimises environmental impact and elevates the passenger experience.

1.4 Scope of this whitepaper:
The complete turnaround

This whitepaper documents the Smart Ramp future ConOps approximately 15 years from now, across the complete 18-step IATA IGOM-aligned turnaround.

The process steps are grounded in the IGOM, the global industry standard with over 221 airline members and 259 ground handling service providers registered on IATA's Operations Portal [5].

The Smart Ramp consortium recommends formal dialogue with IATA on IGOM additions arising from this ConOps, particularly autonomous-equipment standards, digital data exchange (X565, ELIR, NOTOC), biometric boarding interoperability, and the operating model implications of remote supervision.

INBOUND PHASE
STEPS 1 - 9

1 Pre-arrival
2 Aircraft arrival
3 Chocking
4 GPU/PCA
5 Chocking
6 Coning
7 PBB connection
8 Door opening
9 Disembarkation

ON-STAND PHASE
STEPS 10-13

10 Fuelling
11 Catering
12 Cabin cleaning and preparation
13 Toilet & water servicing

OUTBOUND PHASE
STEPS 14-18

14 Load control and loading
15 Passenger boarding
16 Closing doors & predeparture
17 Push back & engine start
18 De-icing

THE CURRENT STATE

2 A PROCESS UNDER STRAIN

THE CURRENT STATE

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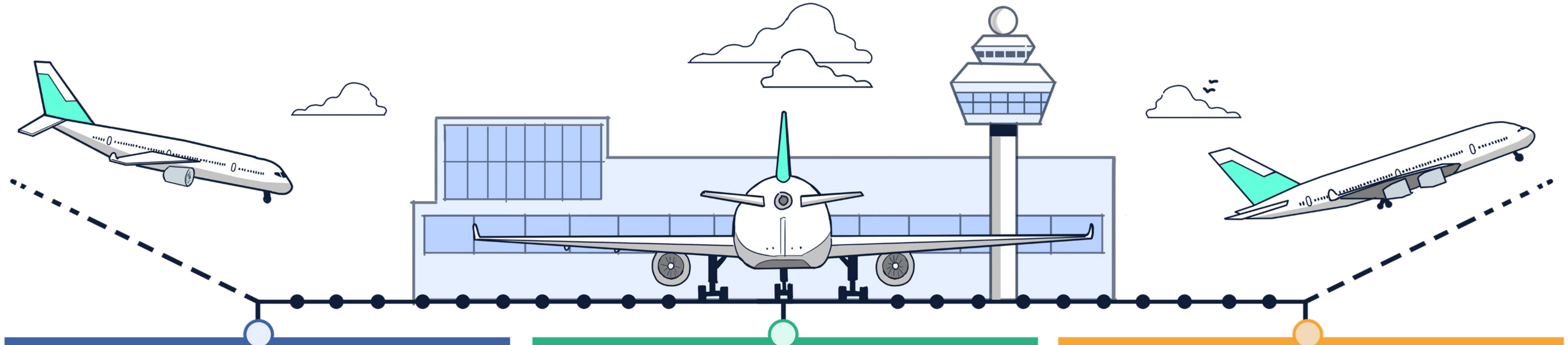
2.1 Introduction:
Deconstructing the aircraft turnaround

This chapter moves from strategic context to operational reality. It provides a detailed analysis of the current state across all three phases — **inbound, on-stand servicing and outbound** — drawing on four days of collaborative workshops covering each phase plus ongoing input from Smart Ramp consortium members. Regional and airline-specific differences exist in how IGOM procedures are implemented, but a striking finding across both workshops is that **the fundamental challenges** are remarkably consistent across geographies, airline types and the three turnaround phases.

2.2 Our framework for analysis:
People, process, technology

We use the **People, Process and Technology (PPT)** framework, a model widely adopted across industries for diagnosing operational challenges, to examine the three core pillars and their interdependencies. For each identified challenge theme, we assess impact across four dimensions: **Cost, Time, Employee and Passenger.**



INBOUND PHASE
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ON-STAND PHASE
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OUTBOUND PHASE
STEPS 14-18

14. Load control and loading
15. Passenger boarding
16. Closing doors & predeparture
17. Push back & engine start
18. De-icing

People, Process and Technology

PEOPLE
Workforce availability, skills, training, physical and mental well-being, organisational culture.

PROCESS
Operational procedures, workflows, communication protocols, coordination mechanisms.

TECHNOLOGY
Equipment, systems, data infrastructure and digital tools that support (or hinder) ramp operations.

IMPACT

Cost

Time

Employee
Health, safety and well-being of the ground handling workforce

Passenger
Delays, missed connections and baggage handling quality

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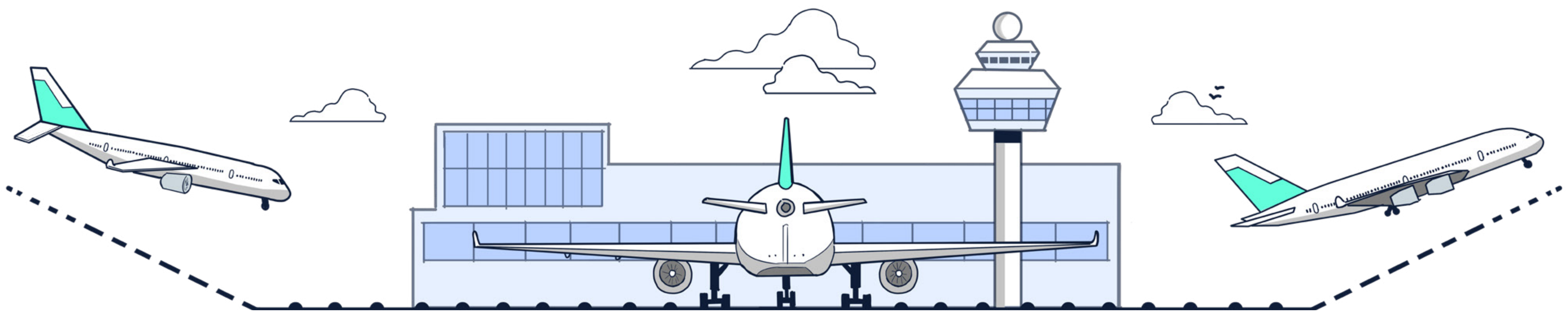
A PROCESS UNDER STRAIN

2.3 The eighteen process steps:
An IGOM-aligned overview

The turnaround — from pre-arrival until the aircraft is airborne — breaks down into eighteen sequential process steps, mapped against the IGOM framework and validated during the two workshops.



INBOUND PHASE			
1	**Pre-arrival**	Pre-Arrival Preparation	FOD check of stand; verify GSE, chocks and cones available and positioned outside ERA; activate VDGS or position marshaller.
2	**Aircraft arrival**	Operations	Guide aircraft via VDGS or marshaller; arrival walkaround; give clearance for GSE to approach.
3	**GPU & PCA**	Operations	Position and secure GPU; safety clearance and pre-connection checks; connect and energise; configure PCA.
4	**Chocking**	Operations	Verify chocks; await full stop; place at nose gear; await engine shutdown; place at main gear; notify crew.
5	**Aircraft coning**	Operations	Place cones within 1 m radius of protected points per IGOM 4.3.2; additional cones per local requirements.
6	**Boarding bridges**	Operations	Pre-position PBB; verify clearance; dock using self-levelling or no-touch method; extend rails and canopies.
7	**Open access doors**	Unloading	Knock twice and signal readiness; cabin crew opens door per aircraft type; engage gust lock; inspect/open cargo doors.
8	**Disembarking**	Unloading	Prepare PBB/stairs; secure route; provide PRM assistance.
9	**Unloading bags & cargo**	Unloading	Brief team on CPM/LDM/OIR; cross-check ULDs against load plan; visual damage checks; transport to baggage hall.

ON-STAND PHASE			
10	**Fuelling**	Servicing	Establish FSZ; connect hoses; commence fuelling; monitor for spillage; disconnect per IGOM 3.2.1–3.2.3.
11	**Catering**	Servicing	Position truck at galley door; offload used carts; load new meals; final checks with crew per IGOM 3.1.3.9.
12	**Cabin cleaning & preparation**	Servicing	Remove waste; clean and disinfect; clean lavatories and galleys; restock; supervisor final inspection.
13	**Toilet & water servicing**	Servicing	Inspect panel and drain waste; flush and recharge; fill water tanks separately; close and check for leaks.

OUTBOUND PHASE			
14	**Load control & loading**	Loading	Produce LIR; transport load; inspect hold; load ULDs/bulk; secure load and close holds; finalise load sheet.
15	**Passenger boarding**	Preparation	Prepare gate; obtain crew clearance; verify identity and scan boarding pass; reconcile and close flight in DCS.
16	**Closing doors & predeparture**	Preparation	Close cabin and cargo doors; retract boarding devices; predeparture walkaround; complete table with cockpit.
17	**Pushback & engine start**	Process	Connect pushback vehicle; departure communication; remove chocks and commence pushback; engine start; disconnect.
18	**De-icing**	Process	Inspect surfaces; position vehicles; apply Type I and (if required) Type IV fluid; provide anti-icing code.

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A PROCESS UNDER STRAIN

2.4 Regional differences and the role of the IGOM

While the IGOM provides a standardised framework, regional and airline-specific variations exist in implementation — driven by local regulation, airport infrastructure, fleet composition, climate and organisational culture. The variations are not inherently problematic but significantly complicate standardisation, particularly during on-stand servicing where multiple stakeholders operate in tight physical and temporal proximity.

Coning and chocking
Different coning configurations and chock placement sequences; some require chocks at both nose and main gear simultaneously, others sequentially.

Boarding bridge operation
Policies differ on who operates the PBB (airline, airport or handler), whether remote or on-site operation is permitted.

Fuelling and into-plane handling
Major handlers (Skytanking, Swissport, Cepsa Aviation) bundle proprietary fuel-management software with contracts. Airline policies on contracted oil-company vs. ITP-only handlers, simultaneous-boarding-and-fuelling rules and SAF blend handling vary.

Catering and cabin cleaning
Meal counts, special-meal handling and cleaning standards vary widely; post-pandemic cleaning standards add 10–20% more ground time depending on the carrier

Load control and W&B
Unloading and loading priorities, ULD handling, DAA policies and W&B sign-off vary. IATA X565/ELIR adoption is early and not yet uniform [8,9].

Passenger boarding
Boarding sequences (back-to-front, WilMA, group-based) and biometric-boarding rules differ significantly by airline and jurisdiction.

Pushback and de-icing
Tractor types (towbar vs. towbarless), 3-way comms requirements, single-engine taxi procedures and de-icing fluid types and HOT tables vary by airline, season and station.

THE CURRENT STATE

6 THEMATIC CHALLENGES IN THE CURRENT OPERATING MODEL

THEME 1
Workforce strain and scarcity

THEME 2
Skill gaps and inconsistent training

THEME 3
Procedural fragmentation and lack of standardisation

THEME 4
Poor communication and information silos

THEME 5
Equipment shortages, legacy systems and environmental impact

THEME 6
Lack of real-time data and limited automation

A PROCESS UNDER STRAIN

2.5.1 People-related challenges

THEME 1
Workforce strain and scarcity

The most pervasive issue is the physical and mental strain on the ground handling workforce, compounded by staff shortages. The work is physically demanding across every step: ramp agents position heavy chocks and cones; cabin cleaners handle heavy waste bags under tight turnaround windows (with reported shortages of up to 37% at major hubs); fuellers work in physically exposed positions around hazardous materials; bag loaders sustain 9 injuries per 1,000 departures and account for 243,000 injuries per year industry-wide [7]; lavatory and water operators face the most unpleasant working conditions on the ramp (up to 60% staff shortage at some stations).

The work happens in all weather, in air filled with aircraft and GSE emissions, under sustained time pressure. Specialised role shortages — PBB operators, marshallers, fuellers, de-icing operators — create critical bottlenecks; in Japan and Germany the labour-shortage situation has become a national policy issue.

Dimension	Severity	Analysis
Cost	High	Sick leave, turnover, recruitment, training and workplace injury compensation. Loading alone drives 9 injuries per 1,000 departures with direct medical, insurance and rework costs [7].
Time	High	Staff shortages cause delays across multiple steps — 10–30 minutes added per turn at degraded cabin-cleaning staffing levels. A single missing specialist can halt the entire sequence.
Employee	Critical	High rates of musculoskeletal injury, falls from height, burnout, occupational stress, and breathing in polluted air [5].
Passenger	Medium	Indirect but consistent — delays during disembarkation, boarding and baggage delivery; missed connections.

THEME 2
Skill gaps and inconsistent training

Effective ramp operations depend on a highly skilled, certified workforce, yet training quality and standardisation remain a significant challenge.

Workshop participants identified inconsistencies in training for PBB operation, VDGS interpretation, FOD checks, airline-specific chocking and coning, certified fuelling, post-pandemic cleaning standards (which add 10–20% ground time), manual W&B, loading instructions (IDX data reveals 16% of mishandling stems from loading failures [5]), pushback signal-and-comms protocols, and certified de-icing application where HOT decisions are safety-critical. The lack of cross-training means the absence of a single certified individual can halt the process.

Dimension	Severity	Analysis
Cost	High	Human error is a leading cause of aircraft ground damage, currently costing the industry ~$5B annually and projected to approach $10B by 2035 [4]; the average catering-truck contact incident alone costs ~$275k.
Time	High	The worst-performing fuellers start 20 minutes before departure vs. 57 minutes for the best — a 37-minute gap that drives directly onto OTP.
Employee	Medium	Inadequate training places employees in high-stress situations where they may feel ill-equipped to perform safely.
Passenger	Medium	Delays from skill-based bottlenecks translate to extended wait times and missed connections.

A PROCESS UNDER STRAIN

2.5.2 Process-related challenges

THEME 3
Procedural fragmentation and lack of standardisation

A core issue is the sheer variety of procedures for the same task. Different protocols exist for coning patterns, chock types, fuel ticketing, catering loading, boarding sequences, baggage unloading, pushback comms and de-icing fluid handling.

Last-minute operational changes — gate changes, aircraft swaps, weather-driven re-routing — invalidate pre-arrival preparations and cascade through the entire turnaround. In the outbound phase, weather-driven de-icing surges compound these effects.

Dimension	Severity	Analysis
Cost	Medium	Lack of standardisation prevents economies of scale in training and equipment. Last-minute gate changes waste deployed resources.
Time	High	Confusion over procedure leads to hesitation. De-icing queueing bottlenecks during storms can hold aircraft tens of minutes per departure.
Employee	Medium	Staff face conflicting procedures, increasing stress and error likelihood.
Passenger	High	Last-minute gate changes are a major source of frustration; process-driven delays impact the entire journey.

THEME 4
Poor communication and information silos

Communication on the ramp is often manual, verbal and siloed. Critical information — chocks-on confirmation, PBB readiness, PRM status, fuelling green light, meal count, LIR, cabin-readiness signal, door-armed status — is relayed via hand signals, radio or paper that is not centrally logged or shared in real time.

The flight deck, ground crew, gate agents, fuel supplier, caterer, cleaner, loader and turnaround coordinator work from different information sets. The Smart Ramp 2025 program found that as much as 80% of innovation project time is spent building custom integrations to bridge these silos rather than generating operational value — a clear signal that the communications architecture is the root cause.

Dimension	Severity	Analysis
Cost	Medium	Miscommunication causes inefficient resource allocation and contributes to damage incidents.
Time	High	Waiting for manual confirmations is a major source of "dead time" — particularly visible in the gap between cabin cleaning completion and boarding start.
Employee	Medium	Lack of reliable information increases stress and uncertainty.
Passenger	Medium	Passengers wait on a fully docked PBB because the cabin crew hasn't received the "all clear", or experience extended baggage wait times.

A PROCESS UNDER STRAIN

2.5.3 Technology-related challenges

THEME 5
Equipment shortages, legacy systems and environmental impact

Many airports and ground handlers suffer from a fundamental shortage of essential GSE; available equipment is often old, manually operated and not integrated with digital systems.
The environmental and health implications are significant: diesel GSE running idle on the apron generates ultra-fine particle pollution; manual de-icing produces glycol runoff; conventional pushback and taxi burn fuel that engine-out and e-taxi alternatives could save (HERON TaxiBot trials show 50–85% taxi-fuel savings on long routes [74]).

The on-stand and outbound phases concentrate the bulk of this environmental footprint. Persistent vendor incompatibility — between VDGS, PBB control, fuelling, catering, DCS, biometric boarding, A-CDM and AODB — prevents a connected, data-driven ecosystem.

Dimension	Severity	Analysis
Cost	Medium	GSE shortages drive delays and emergency procurement costs. Annual ground damage costs ~$10B industry-wide; catering-truck contact alone averages ~$275k [4].
Time	Medium	Equipment shortages and breakdowns directly cause delays; manual data entry and reconciliation add further time, particularly visible in fuel reconciliation, manual load sheets and de-icing records.
Employee	High	Old, manual equipment is more physically demanding and less safe. Diesel exhaust exposes staff to ultra-fine particles linked to cardiovascular and respiratory disease [5].
Passenger	High	Equipment delays directly affect OTP; older equipment is more prone to causing aircraft damage.

THEME 6
Lack of real-time data and limited automation

Across all 18 steps, the workshops identified a striking lack of real-time, automated data capture. Key events — chocks placed, fuelling actually started, cabin cleaning complete, LIR delivered, boarding effectively started, HOT clock — are typically logged manually after the fact, if at all.
This drives downstream problems: disputed delay codes, paper-based W&B that arrives late, radio-call pushback readiness, memory-based HOT tracking. Where automation exists it is overwhelmingly software-only; physical automation is far less mature, and the most labour-intensive tasks (catering loading, cabin cleaning, bulk baggage handling, manual de-icing spraying) remain largely manual. The 2025 benchmark research confirms solutions for almost every category now exist at TRL 7–9; the gap is adoption, not invention. Robotisation of the human-handled bag inside narrow-body holds is currently the most stubborn physical-automation frontier.

Dimension	Severity	Analysis
Cost	High	Manual data capture is labour-intensive and error-prone. Annual ground damage of ~$10B [4] reflects in part the lack of real-time situational awareness.
Time	High	Lack of real-time visibility is the primary obstacle to proactive turnaround management. The 7-minute per-turn potential savings identified by Smart Ramp 2025 turnaround monitoring projects illustrates the latent opportunity.
Employee	Low	Manual data entry is tedious low-value work staff would rather avoid.
Passenger	Medium	The downstream effects — delays, missed connections, baggage errors — degrade and destabilise the passenger experience.

A PROCESS UNDER STRAIN

2.6 Summary:
The challenge landscape

The same six themes recur across all 18 process steps and three phases. The PPT challenges reinforce each other: workforce strain is exacerbated by procedural fragmentation and outdated technology, which deepen skill gaps and amplify communication breakdowns and data deficits.

The on-stand and outbound phases add specific intensities — sustainability pressure, seasonal weather variability, biometric privacy regimes, fuel-handling safety — but no new categories. This thematic consistency is itself the strongest argument for an industry-wide, multi-stakeholder approach to transformation.

2.7 Conclusion:
An operation ripe for transformation

The current state of the turnaround is one of an operation under significant and growing strain, held together by workforce dedication but fundamentally limited by manual processes, fragmented information and ageing technology — and increasingly challenged by sustainability expectations, demographic pressure on labour supply, and weather-driven volatility.

The challenges are systemic but not insurmountable. The factors that cause friction today are the same factors that present the greatest transformation opportunities through automation, digitalisation and a rethinking of how ramp operations are designed and managed. The next chapter introduces the future ConOps.

THE FUTURE STATE

3 A VISION FOR SMART RAMP

A VISION FOR SMART RAMP

3.1 Introduction:
From strain to symphony

Chapter 2 painted a stark picture of the current turnaround. This chapter pivots to the solution: the "to-be" vision for the Smart Ramp 15 years out, a fundamental reimagining of the ramp environment, shifting from a reactive, labour-intensive operation to a proactive, data-driven, highly automated ecosystem across all 18 steps.

> The Smart Ramp future is not **about replacing people** with machines. It is about elevating people from manual execution to strategic supervision, while creating an operation that is **safer, faster, more resilient and dramatically more sustainable**. The technology is ready.
>
> SMART RAMP CONSORTIUM - WORKSHOP VISION STATEMENT

3.2 The core paradigm shifts:
Six building blocks of the future ramp

Six fundamental paradigm shifts form the building blocks of the Smart Ramp. They are not isolated innovations but deeply interconnected transformations that together create a new operational architecture. All six apply consistently across inbound, on-stand and outbound, though they manifest differently in each.

Building blocks:

A remote command centre
People move from the ramp to a centralised control room, supervising multiple turnarounds remotely via a digital twin and AI-assisted decision-making.

Autonomous robotics and vehicles
Physical tasks performed by a modular fleet of autonomous robots, tugs, boarding bridges, refuellers, cleaners and de-icers operating at Level 4–5 autonomy.

A digital twin and orchestration layer
A real-time digital twin that provides the operational model and context layer and an AI-powered orchestration layer that converts data into actionable scenarios for human decision-makers.

A new data and connectivity stack
A private wireless network, pervasive IoT sensors and a dedicated data layer providing the secure, high-speed foundation.

The elimination or absorption of several manual steps
Several manual steps are entirely eliminated or absorbed into other automated processes.

Transformation of ramp roles
The workforce evolves from manual labourers to skilled supervisors, with a new Service Provider model for equipment-as-a-service.

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The command centre model — from on-stand execution to remote supervision

The most profound transformation is the relocation of human oversight from the physical ramp to a centralised remote Command Centre. The majority of personnel are no longer on the stand, exposed to safety hazards, jet blast, extreme weather and poor air quality; they transition to supervisory roles in a controlled indoor environment, overseeing multiple turnarounds simultaneously.

Turnaround Coordinators monitor progress across the full 18 steps through a digital twin that reflects the live state of the turnaround and provides the context for simulation. AI agents operating in the orchestration layer use that twin to model scenarios, compare options, and present recommended actions to the human supervisor.
A conversational AI interface allows supervisors to query the operation, ask "what if" questions, and understand agent-generated recommendations. For irregular operations a specialised Disruption Team is on standby for physical intervention. This shift directly addresses workforce strain and scarcity by moving staff indoors and enabling one coordinator to oversee multiple stands.

Autonomous robotics and vehicles — a modular fleet of intelligent machines

The physical work is largely performed by a new generation of intelligent, interconnected and autonomous systems. We envisage a modular autonomous fleet where individual units can perform multiple functions, improving utilisation and reducing total ramp vehicles. The fleet spans the entire turnaround.

System	Function	Key characteristics
Multi-Functional FOD Robot	FOD detection, sweeping; potentially wing-walking, coning, chocking	Autonomous, multi-role, 24-hour operation
Autonomous Chock-Bots	Navigate to landing gear and place/lock chocks	Vacuum-based mini-robots; can integrate with GPU at nose gear, and potentially combinable with autonomous pushback truck
Robotic GPU/PCA Connector	Connect ground power and pre-conditioned air	All-in-one robot; or GPU/PCA embedded in autonomous PBB
Autonomous Boarding Bridges	Extend, connect, retract guided by sensors and data	Zero docking wait; integrated GPU/PCA; passenger experience platform
Autonomous Tugs & ULD Carriers	Transport baggage and cargo between aircraft and terminal	Level 4–5; just-in-time arrival via orchestration
Autonomous Passenger Buses	Transport passengers from remote stands to terminal	Driverless; coordinated with Command Centre
Autonomous Wheelchairs	Door-to-gate mobility for PRM passengers	Summoned via app/airline data; autonomous navigation
Humanoid / Specialist Bag Robots	Bulk-load and unload bags in narrow-body holds	Addresses the most physically demanding ramp task
Electric / Autonomous Refueller	Deliver Jet A1 or SAF with electric drivetrain and digital ITP	Zero apron emissions; digital fuel ticketing; SAF-compatible
Single-Operator Catering Platform	Galley servicing with smart hydraulics and self-levelling	Electric chassis; integrated meal-count data
UV-C / Spray Cleaning Robot	Autonomous cabin disinfection during turn	Self-navigating; verifies dose and coverage
Electric Pushback Tractor / TaxiBot	Electric towbarless tractor; engine-off taxi to runway	Zero gate emissions; 50–85% taxi-fuel savings on long routes [74]
Autonomous / LIDAR-Assisted De-icer	Operator-assisted or autonomous spraying with LIDAR scanning	Electric chassis; recycled-glycol compatible; reduced fluid use
Drone Aircraft Walk-Around	Automated GVI of fuselage and critical surfaces	FAA/EASA-accepted at multiple airlines [65,66,68,69]

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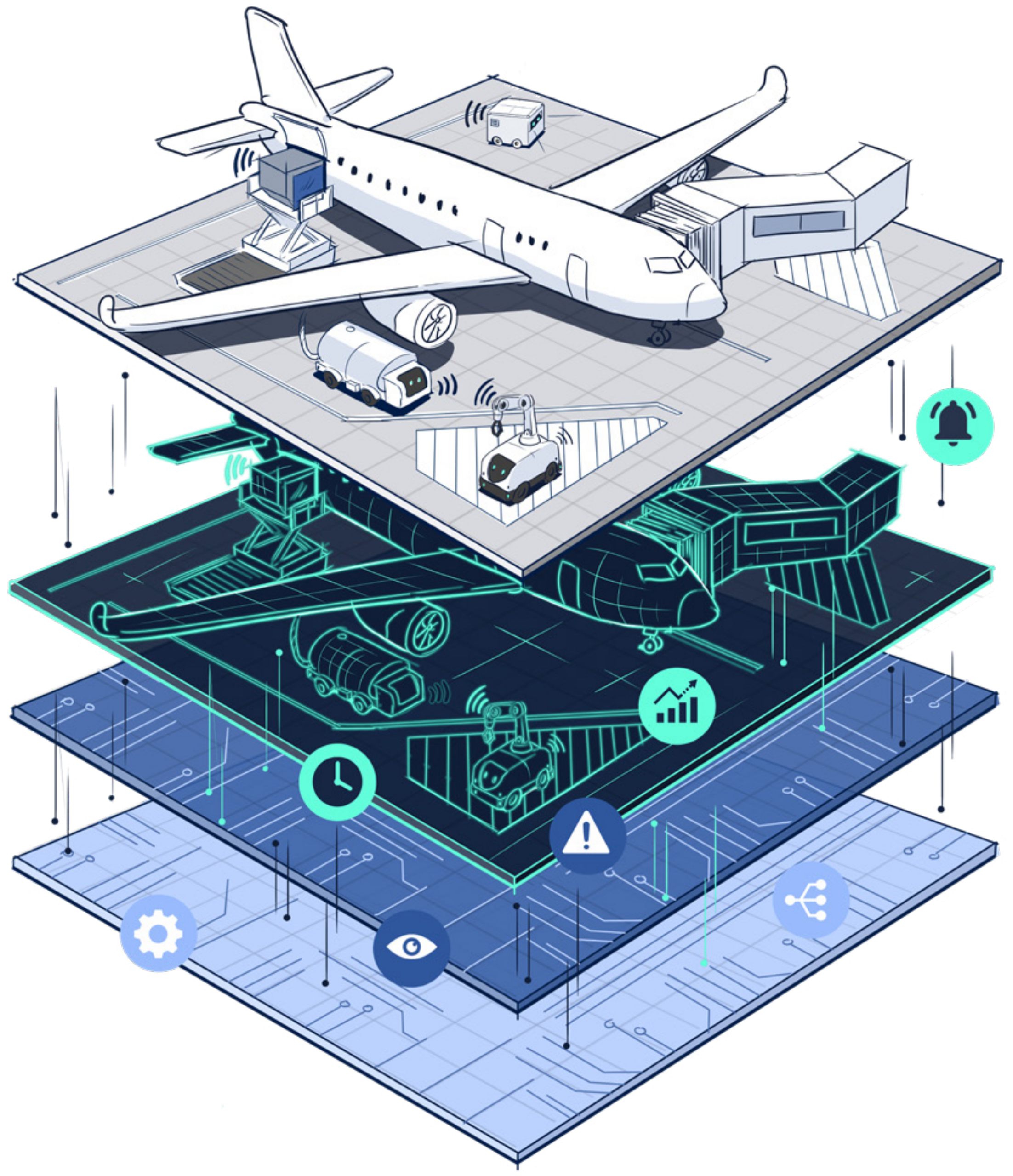
The digital twin and orchestration layer, the brain of the operation

If the autonomous fleet is the hands, the digital twin and orchestration layer together act as the "brain" directing their actions.
The wide-ranging digital twin is a persistent, real-time virtual model of the physical ramp, integrating data from LiDAR, computer vision, IoT sensors, aircraft systems and airline operational databases. It spans the full 18 steps — from FOD readiness through fuel-order reconciliation, biometric boarding flow, load-sheet sign-off and post-de-icing HOT tracking. It provides complete situational awareness, enables predictive operations, and replaces physical safety systems (most strikingly: physical safety cones replaced by digital twin enabled safety controls such as dynamic digital geo-fencing that automatically halts any vehicle breaching the boundary). The orchestration layer atop the digital twin converts data streams into actionable decision scenarios. It does not make autonomous decisions on complex matters; it presents options, models outcomes, and supports the human in the loop. The aircraft itself becomes an active participant, communicating its operational requirements directly to the data layer, the digital twin models them, and the orchestration layer drives the coordinated response.



The new data and connectivity stack, the foundation of the smart ramp

The ecosystem rests on robust, secure, high-speed connectivity. Workshop participants identified non-negotiable infrastructure requirements:

Requirement	Description
Private Wireless Network	Dedicated high-bandwidth, low-latency network. Private 5G is the emerging standard [96,97,98].
Pervasive IoT Sensor Layer	Dense network of IoT sensors, computer vision and LiDAR — extending to in-cabin lavatory and water sensors that signal condition-based service need.
Dedicated Data Layer	Purpose-built platform for ingesting, processing and storing operational and maintenance data.
Analysis and Interpretation Layer	AI-powered analytics transforming raw data into actionable insights.
Open Data Exchange Standards	Adoption of IATA AHM 908, AIDX, X565, ELIR and digital NOTOC across all members to prevent vendor lock-in [8,9].
Secure Communication Protocols	End-to-end encrypted, GDPR-compliant.
Airport Energy Infrastructure	Airport evolves into energy provider for electric GSE, autonomous vehicles, electric refuellers and de-icers, and future electric/hybrid/hydrogen aircraft [15,84,85,86].

A real-time digital twin and an AI-powered orchestration layer that converts data into actionable scenarios for human decision-makers.

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Process elimination and integration, doing less to achieve more

When the ramp is populated by autonomous systems rather than people, many safety and coordination processes that exist solely to protect human workers — or to compensate for the absence of real-time data — become redundant.

Current process	Future state	Rationale
Marshalling	Phased out	VDGS is automatically activated; pilot communicates directly with Command Centre.
GPU & PCA Connection (separate step)	Eliminated / Absorbed	GPU and PCA embedded in autonomous PBB; all-in-one robot at non-bridge stands.
Physical Coning	Phased out	Dynamic digital geo-fencing replaces cones; automatic halt on boundary breach.
Manual Door Knocking	Phased out	Digital visual indicator and IoT notification to cabin crew when PBB is safely docked.
Manual Chocking	Automated	Autonomous chock-bots place and lock chocks; monitored remotely.

Current process	Future state	Rationale
Paper Fuel Ticketing & Manual Reconciliation	Phased out	Digital ITP platforms (i6/Fusion6, Skymetrix) replace paper with real-time order, reconciliation, SAF tracking [14].
Manual Catering Coordination (two operators)	Reduced / integrated	Single-operator electric platforms; AI demand forecasting sized to actual consumption [21].
Manual Cabin-Ready Sign-Off	Phased out	Computer-vision verification confirms cabin readiness automatically — closes the chronic Step 12/15 synchronisation gap.
Scheduled Lavatory & Water Servicing	Replaced	In-cabin IoT sensors trigger condition-based service; trucks only arrive when needed; electrified chassis.
Manual W&B / Paper LIR	Phased out	IATA X565 and ELIR digitise W&B and LIRs end-to-end; digital NOTOC. Early adopters report up to 80% fewer loading errors [9].
Manual Boarding-Pass Scan	Phased out	Biometric pass-through at the gate (SITA Smart Path, Star Alliance Biometrics, Face Express — all TRL 9 today) [47,54,60].
Pre-Departure Manual Walk-Around (per turn)	Replaced	Automated drone GVI or stand-mounted camera/LiDAR; manual walk-around retained only for post-event inspection [65–70].
Conventional Engine-Start During Pushback	Replaced	TaxiBot or on-board e-Taxi eliminates the opposing-forces risk and saves 50–85% taxi fuel [74,75].
Diesel Pushback Tractor with Driver	Phased out	Remote-controlled electric tractors (Mototok, Goldhofer ATLAS 2 / PHOENIX E) supervised from the Command Centre [76,78].
Manual De-icing Application	Reduced	LIDAR-assisted, operator-supervised spraying (Vestergaard OPTIM-ICE class) reduces fluid use and exposure; automatic HOT tracking [88].

The phased out process steps have a cascading positive effect: fewer tasks in the sequence, a shorter critical path, fewer sources of delay and human error. Particularly elegant collapses are GPU/PCA into the autonomous PBB, digitisation of fuel tickets, digital W&B, and the move from pushback-plus-engine-start to e-taxi — each combining two or more time-consuming processes into a single automated action.

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Transforming roles, from manual labour to strategic supervision

The transition fundamentally reshapes roles. The Smart Ramp workshops deliberately defined the functions required in the future but did not assign roles to specific organisations (airline, airport or handler), recognising that optimal assignment will vary by airport and market.

Future role	Key responsible	Scope
Turnaround coordinator	Supervises autonomous operations across all 18 steps via the digital twin; decides on AI-generated scenarios; deploys Disruption Teams.	Multi-stand from the Command Centre
Disruption / Rush team	On standby for physical deployment during irregular operations. Cross-trained across multiple domains.	Shared resource across multiple stands
Supervisor of autonomous vehicles	Oversees the autonomous fleet — refuellers, de-icers, bag robots — monitoring system health and edge cases.	Fleet-wide from the Command Centre
Service provider	Provides and maintains autonomous equipment under an equipment-as-a-service model.	New role; organisation type left open
Cabin readiness supervisor	Remotely supervises UV-C and spray robots; signs off cabin-ready to start boarding.	Multi-stand from the Command Centre
Biometric flow supervisor	Oversees biometric pass-through; handles exceptions; final passenger counts.	Multi-gate from gate-side or Command Centre

The Service Provider concept introduces a new business model: the complexity of owning, maintaining and certifying autonomous equipment is abstracted away from the operator, mirroring "power-by-the-hour" in aviation maintenance and lowering the barrier to entry.

Current role	Future state	Rationale
Marshaller	Reshaped	The role will evolve to focus on higher-value strategic tasks in alignment with automatic VDGS activation and digital twin guidance.
Chock Handler	Reshaped	The role will evolve to focus on higher-value strategic tasks in alignment with autonomous chock-bots, monitored remotely.
Cone Placer	Reshaped	The role will evolve to focus on higher-value strategic tasks in alignment with digital geo-fencing replaces physical cones.
PBB Operator	Transformed	Remote supervisor managing multiple autonomous bridges.
GPU/PCA Operator	Reshaped	The role will evolve to focus on higher-value strategic tasks in alignment with robotic connection or integration into autonomous PBB.
Bus Driver	Reshaped	The role will evolve to focus on higher-value strategic tasks in alignment with autonomous passenger buses.
Wheelchair Assistant	Transformed	Autonomous wheelchairs; human role shifts to passenger care.
Baggage Handler (heavy lifting)	Reduced	Humanoid robots and automated systems handle most demanding loading.
Fueller / Into-Plane Operator	Transformed	Electric and (long-term) automated refuelling; remote supervisor handling exceptions, hydrogen pilots, SAF allocation.
Catering Loader (two-person)	Reduced	Single-operator electric platforms; further reduction as cobots take over trolley exchange.
Cabin Cleaner	Transformed	Cabin Readiness Supervisor working alongside UV-C and spray robots.
Lavatory & Water Operator	Transformed/ reduced	Electric trucks plus IoT-driven scheduling; consolidated multi-service supervision.
Loadmaster	Transformed	Digital W&B / ELIR / NOTOC do the calculation; remote Load Control Supervisor for exceptions and dangerous goods.
Gate Agent (boarding)	Transformed	Biometric Flow Supervisor for exceptions and passenger care.

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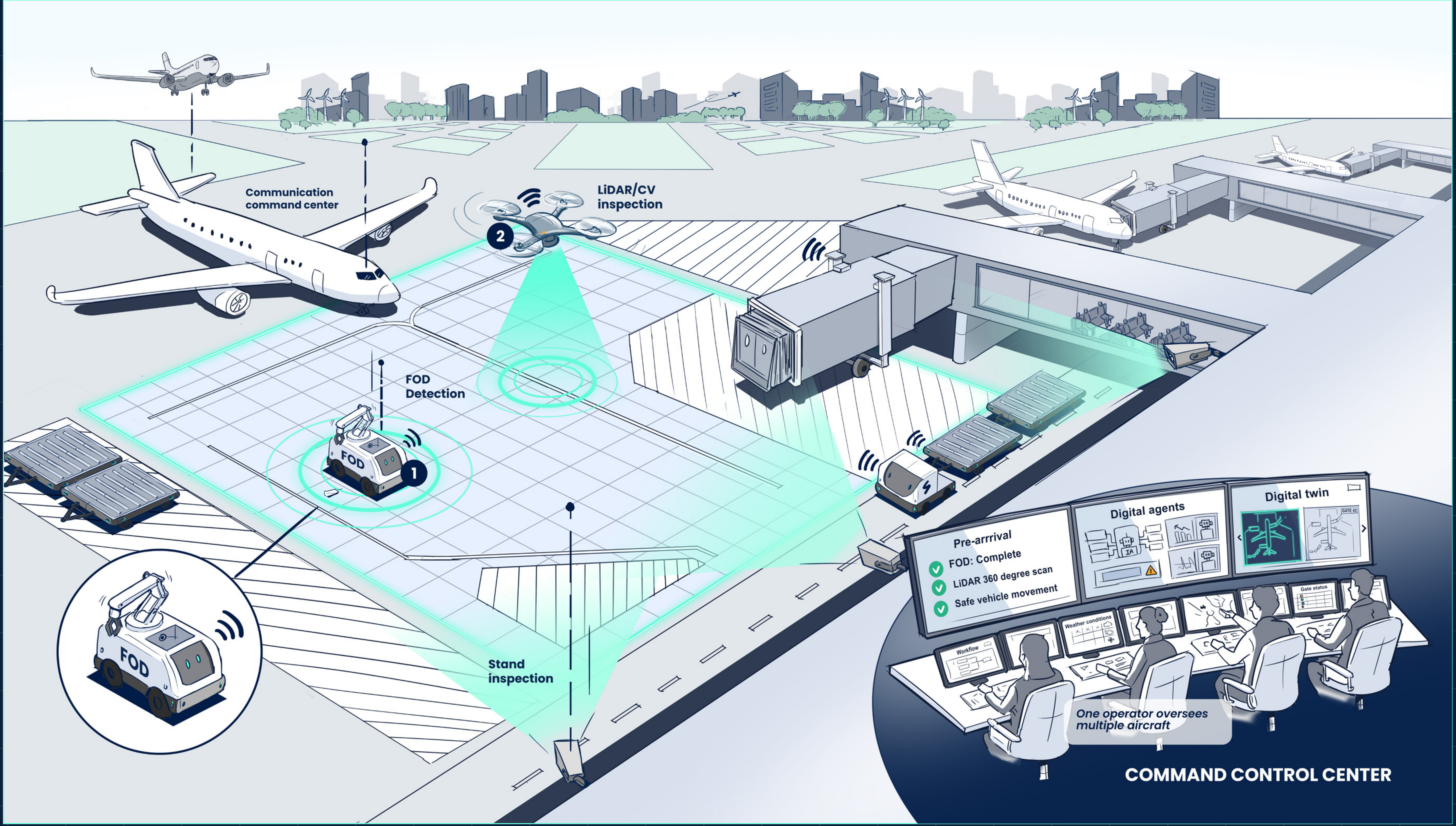
3.3 The eighteen steps reimagined:
A day on the future ramp

This section revisits each of the eighteen steps. Steps 1–9 reflect the inbound vision validated in Workshop 1 and v1.0 of this whitepaper; steps 10–18 reflect the on-stand and outbound vision developed in Workshop 2 (March 2026).



1 **Pre-arrival**

A predictive, autonomous system continuously inspects the ramp and deploys all required GSE automatically before aircraft arrival.

2 **Aircraft arrival**

The digital twin coordinates aircraft docking, automated inspections, and safe vehicle movement.

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3.3 The eighteen steps reimagined:
A day on the future ramp

We use the **People, Process and Technology (PPT)** framework, a model widely adopted across industries for diagnosing operational challenges, to examine the three core pillars and their interdependencies. For each identified challenge theme, we assess impact across four dimensions: **Cost, Time, Employee and Passenger.**

People, Process and Technology (PPT) framework

PEOPLE
Workforce availability, skills, training, physical and mental well-being, organisational culture.

PROCESS
Operational procedures, workflows, communication protocols, coordination mechanisms.

TECHNOLOGY
Equipment, systems, data infrastructure and digital tools that support (or hinder) ramp operations.

	Turnaround process step	Description	People	Process	Technology
1	**Pre-arrival** 	Fully automated and predictive. A multi-functional robot has performed a continuous 24-hour FOD sweep. The digital twin reflects real-time and predicted GSE availability; orchestration uses this to identify gaps and coordinate actions assuring GSE availability. GSE arrives autonomously through intelligent pooling. No human presence on the ramp.	Turnaround Coordinator monitors remotely; AI provides decision choices; Disruption Teams on standby.	Periodic FOD checks replace manual inspections; orchestration deploys resources automatically.	Multi-functional FOD robot; modular autonomous fleet; predictive GSE maintenance.
2	**Aircraft arrival** 	The digital twin communicates apron safety. VDGS is automatically activated — no human marshaller. The pilot has integrated communications with the Command Centre. Automated drone or stand-mounted LiDAR/CV inspection performs the initial walk-around. LiDAR + CV collision avoidance ensures safe vehicle movement.	No marshaller on stand; pilot communicates with the command centre.	Remote oversight; automated collision avoidance.	Drone or FOD-vehicle inspection; LiDAR + CV; automatic VDGS activation; data security protocols.

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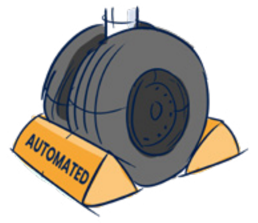
3 GPU & PCA connection

Power and conditioned air connect autonomously based on aircraft requirements.

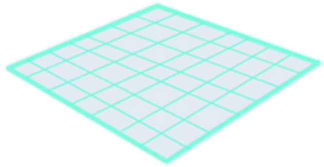
4 Chocking

Autonomous chock-bots secure the aircraft with centimetre-level precision.



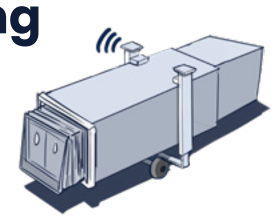
5 Aircraft coning

A dynamic digital geo-fence replaces physical safety cones.



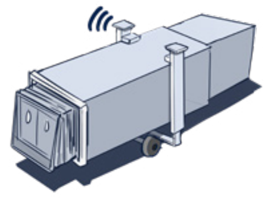
6 Boarding bridge positioning

A secure digital handshake authorises door opening and passenger access.



7 Open access doors

The digital twin coordinates aircraft docking, automated inspections, and safe vehicle movement.

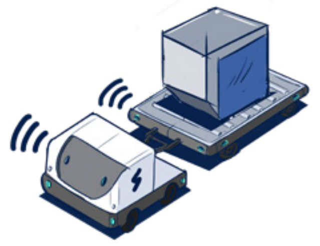


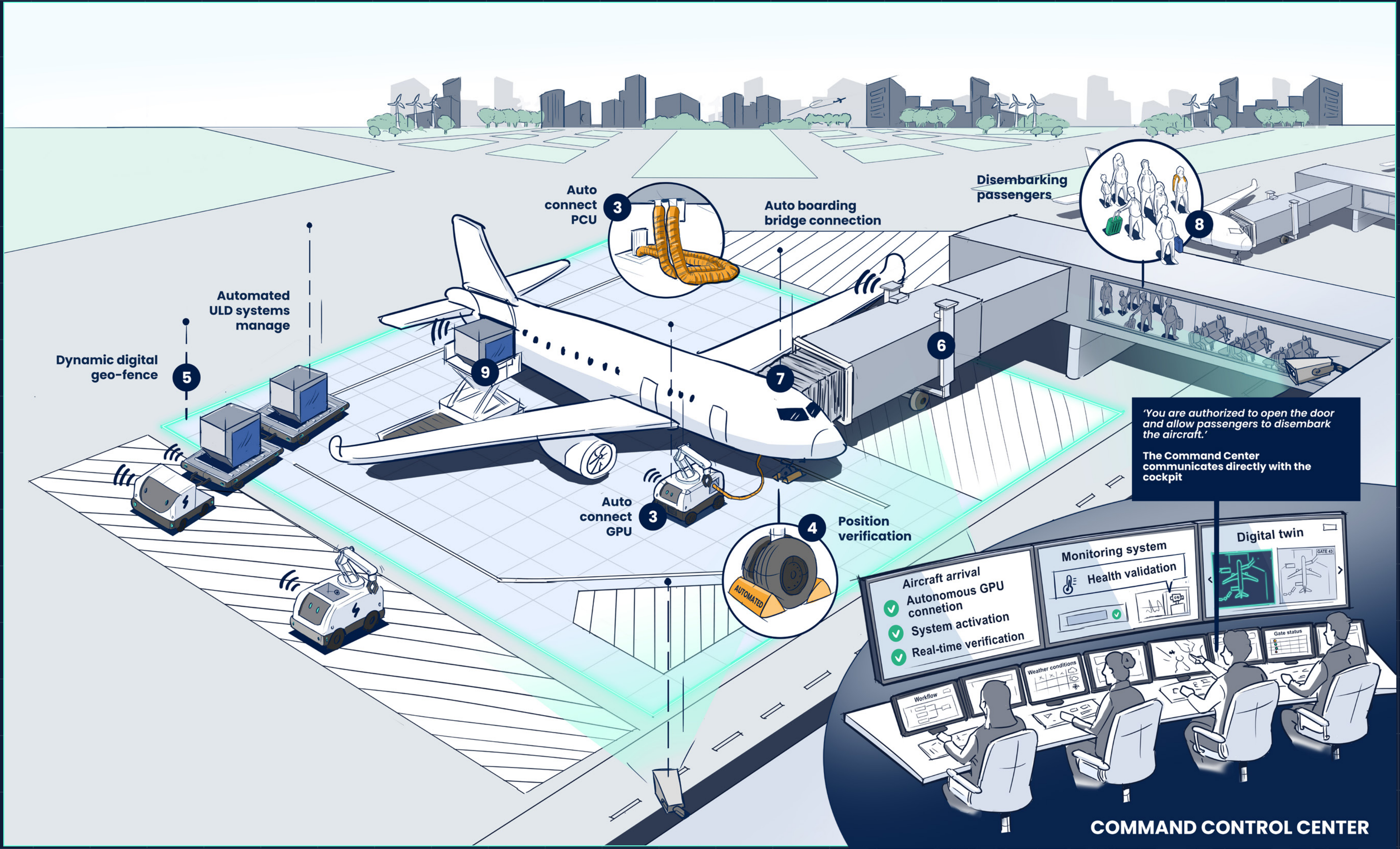
8 Disembarking

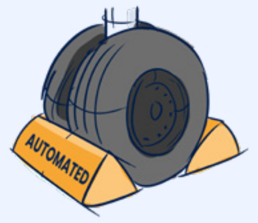
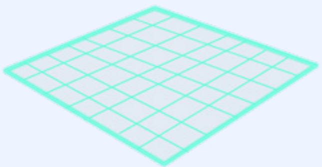
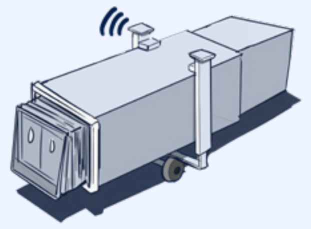
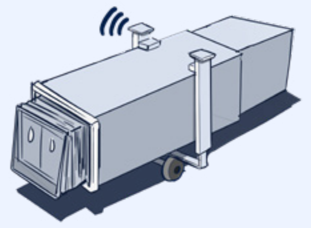
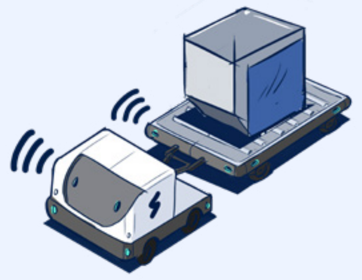
Passengers disembark via the automated bridge.

9 Unloading bags & cargo

Humanized robots or electric autonomous vehicle to unload transport baggage and cargo.





	Turnaround process step		Description	People	Process	Technology
3	**GPU & PCA connection**		Effectively eliminated as a separate manual step. GPU and PCA are embedded in the autonomous PBB. The aircraft communicates requirements (PCA temperature, GPU needs) directly to the digital twin. For non-bridge stands a single all-in-one robot autonomously connects power and air.	Remote oversight only; rush teams on standby.	Aircraft communicates requirements to the digital twin; PBB-integrated GPU/PCA eliminates the discrete step.	FOD/sweeper/GPU all-in-one robot; GPU-charged TaxiBot or robotic GPU connector for non-bridge stands.
4	**Chocking**		Once the aircraft reaches its final stop, its position is identified to centimetre-level accuracy by the digital twin. Small vacuum-adhesion chock-bots dispatch from their base and place themselves at main and nose gear. Monitored remotely; Aircraft chocking the physical process has been phased out	No employee for chocking; staff move to control-room roles.	Digital twin identifies aircraft type and position; chocks autonomously navigate and lock.	Vacuum-based chock mini-robots; combined chock/GPU robot at nose gear; multi-role transformation across robots.
5	**Aircraft coning**		Aircraft coning the physical process has been phased out. The digital twin maintains the live airside context; the orchestration layer defines dynamic geo fencing calibrated to aircraft dimensions, enforced by autonomous systems. ;any autonomous vehicle approaching is automatically halted. Remaining human staff (during irregular operations) use digital glasses or wearables for safety alerts.	Human oversight replaces physical cone placement; multi-ramp monitoring from the control room.	Autonomous digital fencing; automatic vehicle shutdown on breach.	Digital airport map and gate layouts in the digital twin; live vehicle location tracking; digital glasses for remaining staff.
6	**Boarding bridge positioning**		The autonomous PBB extends and connects to the door with zero human intervention and zero docking wait. Monitored by a Command Centre supervisor overseeing multiple bridges simultaneously. The bridge is a multi-functional platform: GPU/PCA embedded; digital screens for personalised content.	Remote oversight of multiple bridges; new stakeholders (Marketing, Brand, Retail).	Geo-fencing-triggered auto-connection; PBB and stairs attached autonomously; GPU/PCA embedded.	Sensors, CV, passenger data; autonomous bridges; visual indicator for cabin crew.
7	**Open access doors**		The physical "knock" is replaced by a secure digital handshake. Once the autonomous PBB is safely docked, IoT sensors and CV confirm the seal and a visual indicator signals the cabin crew. Notification flows via data communication. No ground staff at the door.	No operator inside the boarding bridge; fully automated with remote oversight.	Visual indicator notification; digital handshake replaces manual confirmation.	IoT sensors confirming PBB seal; CV for door status; data communication to cabin crew.
8	**Disembarking**		Passengers disembark via the automated bridge. PRM passengers use an autonomous wheelchair summoned via app or airline data. For remote stands, an autonomous bus docks with autonomous stairs and coordinates departure with the Command Centre. Four disembarkation modes are defined: bridge, stairs, autonomous bus, autonomous wheelchair.	Fewer people overall; heavy physical work performed by autonomous systems.	Four modes; autonomous bus receives passenger count and departs.	Autonomous PBB and stairs; autonomous bus; autonomous wheelchair with boarding-pass scanning.
9	**Unloading bags & cargo**		For narrow-body aircraft with bulk-loaded baggage, a humanoid or specialist robot extracts bags — addressing the single most injury-prone ramp activity [7,33,41,42,43]. For wide-body, automated ULD systems manage offloading. Autonomous tugs/carts arrive just-in-time to transport to the baggage hall.	Fewer or no employees for heavy lifting; fewer drivers for tugs and carts.	Autonomous unloading; just-in-time coordination by orchestration.	Humanoid/specialist bag-handling robots; Level 4–5 autonomous tugs, ULDs, carts.

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10 **Fuelling**

Autonomous refuelling is coordinated and monitored through digital safety systems.

11 **Catering servicing**

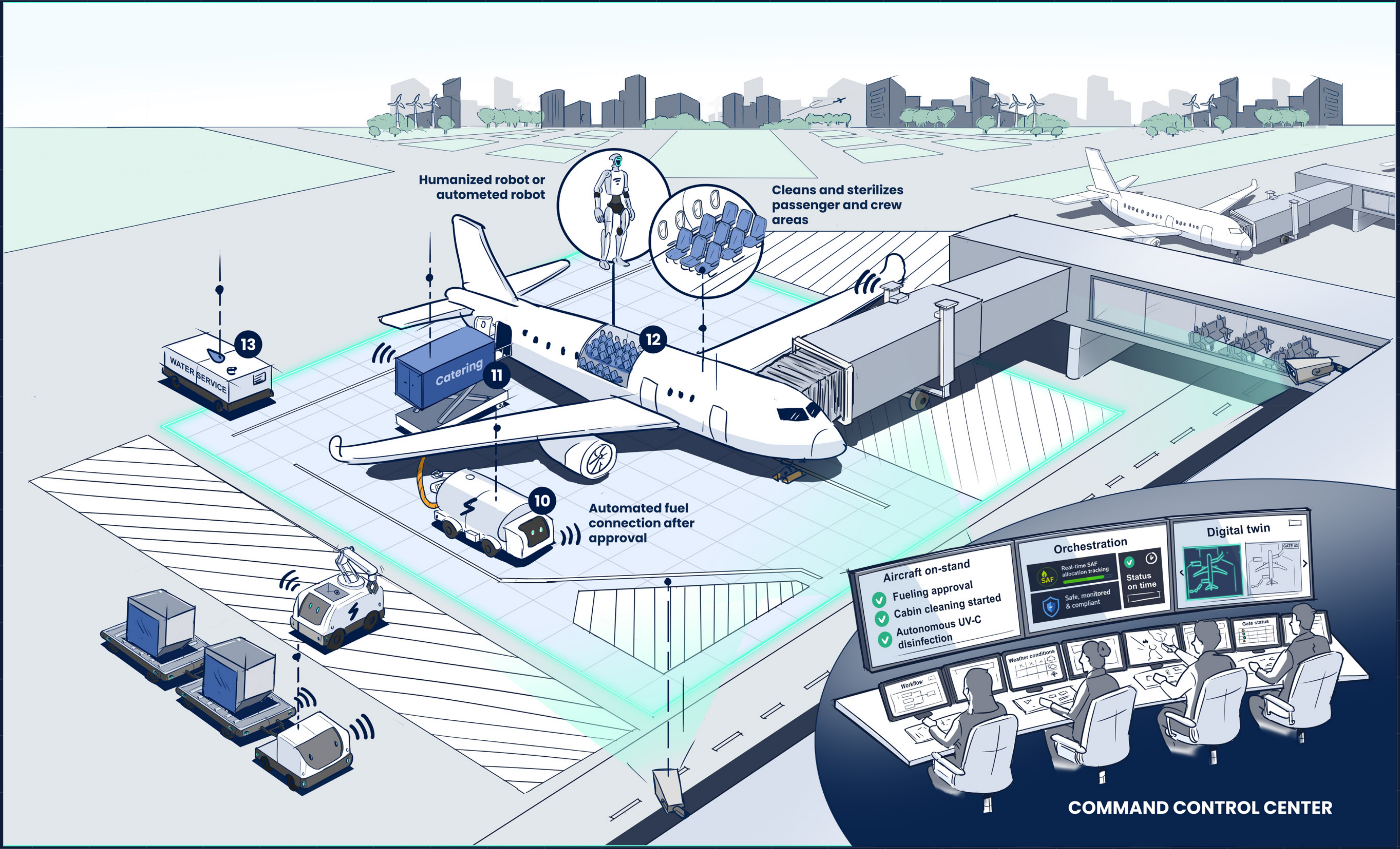
Smart catering delivers and replenishes supplies based on real-time demand.

12 **Cabin cleaning & Preparation**

Autonomous systems clean, disinfect, and prepare the cabin for boarding.

13 **Toilet & water Servicing**

Condition-based servicing replenishes water and waste systems only when needed.



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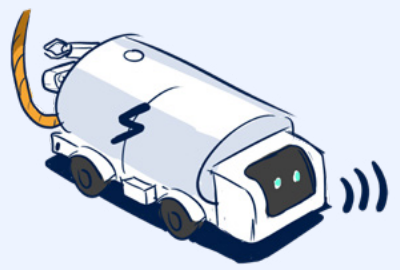
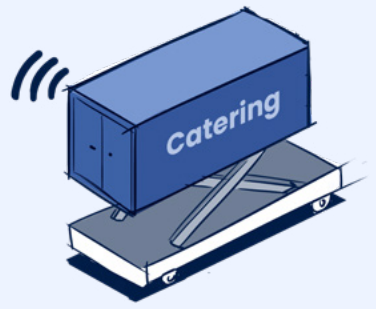
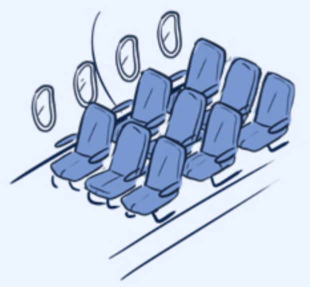
#	Step		Description	People	Process	Technology
10	**Fueling**		Fuelling becomes a quiet, autonomous operation. An autonomous refueller, coordinated by the orchestration layer based o digital twin's live view with the aircraft's fuel data already on file, arrives inside the dynamic geo-fence without a marshaller. A digital ITP platform exchanges quantity, SAF blend attributes and reconciliation data with the airline DCS automatically — paper tickets eliminated. Hose connection remains physical for the foreseeable future (no commercial robotic fuel arm yet), performed by a single operator using ergonomic sensor-assisted couplings; smart hydrant pits monitor pressure and seal integrity in real time. Where IGOM rules permit, fuelling proceeds in parallel with boarding under digital safety oversight. The Fuelling Operations Supervisor monitors multiple refuels and tracks SAF allocation against airline commitments [10].	Single on-stand operator supervised remotely. No paper tickets, no exhaust exposure, no manual reconciliation.	Geo-fenced FSZ; digital ITP order/dispatch/reconciliation; automated SAF book-and-claim; concurrent boarding under digital oversight.	Electric refueller [11,12,13] or smart hydrant; digital ITP platform [14]; IATA CADO [10]; IoT seals on hydrant pits; sensor-assisted couplings.
11	**Catering Servicing**		Catering is delivered by single-operator, electric high-lift trucks with smart hydraulics and collision-avoidance sensors. Meal counts flow directly from the airline DCS into the caterer's system; AI demand forecasting sizes the load to actual expected consumption rather than worst-case, eliminating wasted carts and millions of meals of food waste [21]. Just-in-time arrival; digital sign-off with cabin crew. In the longer-term scenario a galley cobot inside the truck handles trolley exchange.	One ramp operator instead of two; reduced physical strain; catering planner consolidates into an AI-assisted demand forecaster.	Just-in-time arrival; AI demand forecasting reduces over-catering; digital crew sign-off; standardised across airlines.	Electric single-operator high-lift truck [16,17,18,20]; collision-avoidance sensors; AI demand-forecasting platform [21,22]; future galley cobot.
12	**Cabin Cleaning & Preparation**		Cabin cleaning runs in parallel with catering and refuelling, not sequentially. An autonomous UV-C disinfection trolley sweeps the cabin while a small antimicrobial spray robot applies the surface treatment. A waste-handling cobot removes bags and replenishes seat pockets and lavatories from a pre-staged service cart. CV verifies coverage automatically, generating a digital cabin-readiness signal that the gate uses to start boarding — closing the chronic synchronisation gap between cleaning and boarding. Restock inventory is held in pre-packed kits scanned via RFID.	From multi-person crew under time pressure to one or two Cabin Readiness Supervisors per console plus a small physical Disruption Team.	Parallel execution with catering and refuelling; automated cabin-ready signal triggers boarding; RFID inventory; CV-verified cleaning.	Autonomous UV-C trolley [23,24]; antimicrobial spray robot [25]; waste cobot; CV cameras in cabin; RFID restock kits; shared terminal/cabin cobot fleet [27,28,29,30].
13	**Toilet & Water Servicing**		The most under-served step in today's turnaround becomes condition-based rather than scheduled. In-cabin IoT sensors monitor lavatory waste-tank level, water-tank quality, and methane/odour as proxy for service need. The orchestration layer dispatches an electric service truck only when needed — never on a fixed cycle — eliminating the bulk of wasted trips. The truck arrives just-in-time, separated from any potable-water truck. A single multi-task supervisor handles both lavatory and water operations from an integrated workstation, with biohazard segregation preserved through workflow and PPE rather than two separate certified operators. Connection remains physical in the medium term; the operator uses ergonomic, sensor-assisted couplings and digital water-quality verification.	Single integrated service supervisor instead of two specialists. Far fewer trips, far less time on the ramp, better biohazard protection.	Condition-based service dispatch; integrated lavatory + water operating model; digital water-quality verification.	In-cabin IoT sensors (methane, level, presence); electric lavatory and potable-water trucks [34]; LoRaWAN or private 5G backhaul; digital water-quality test integrated with airline maintenance logs.

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14 **Load control & cargo / Baggage loading**

Autonomous vehicles and robots handle loading activities, while supervisors manage exceptions and monitor operations

15 **Passenger boarding**

Boarding becomes a seamless biometric process with no manual boarding pass checks.

16 **Closing doors & predeparture**

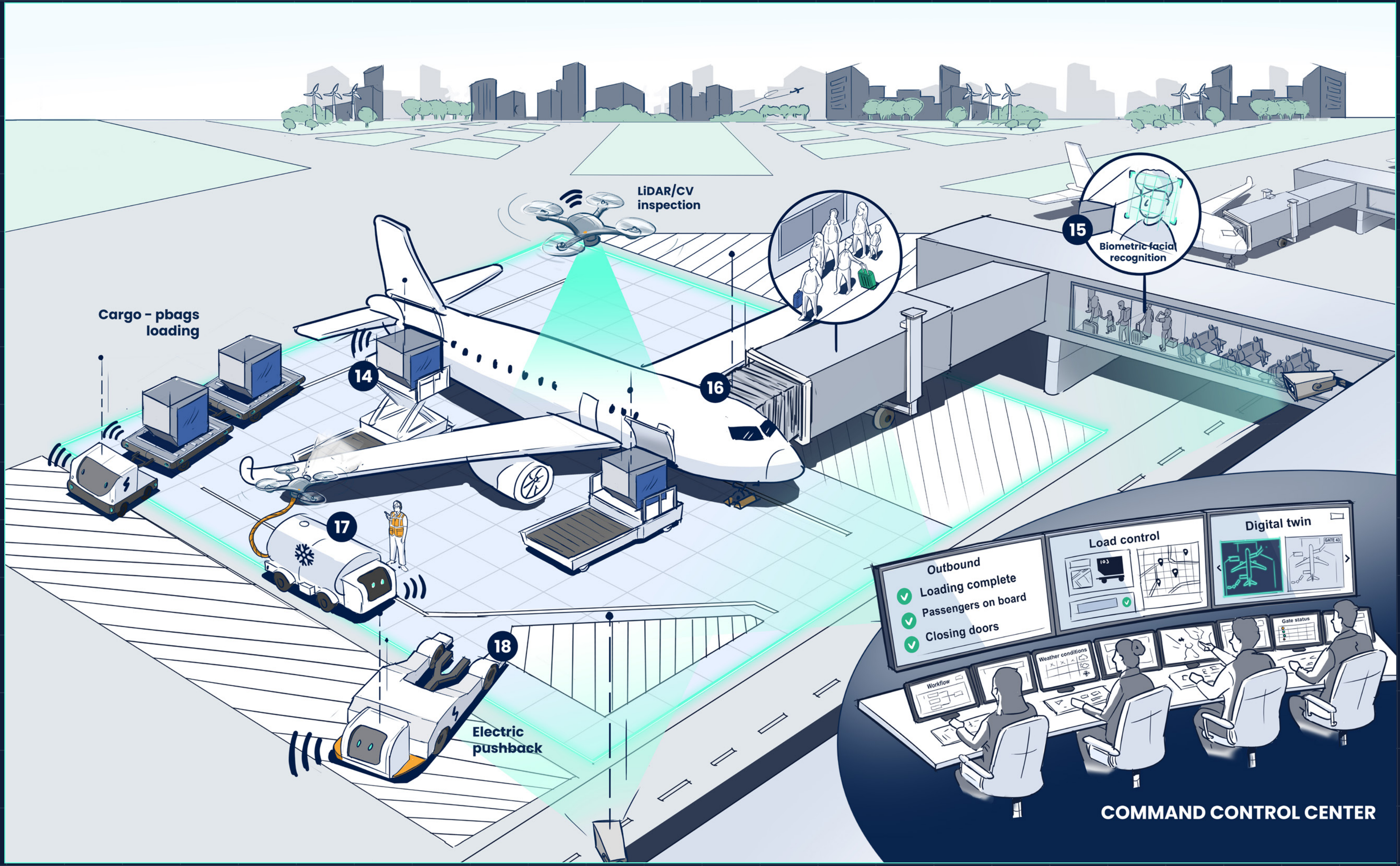
Pre-departure checks become automated. Sensors, cameras, and drones verify readiness before digital sign-off.

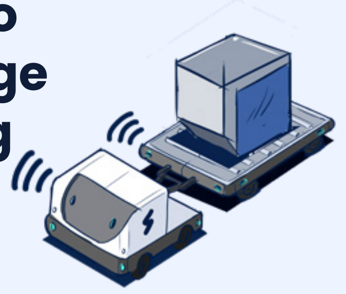
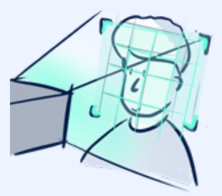
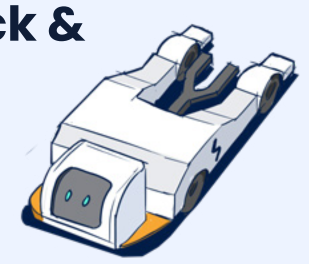
17 **Pushback & engine Start**

Pushback operations are replaced by TaxiBots. Engine start moves closer to take-off, reducing fuel consumption and emissions.

18 **De-icing**

De-icing becomes smarter and more sustainable. Automated systems optimize treatment, timing, and resource usage.



	Turnaround process step	Description	People	Process	Technology
14	**Load control & cargo Baggage loading** 	Load control runs end-to-end on digital standards. IATA X565 W&B, ELIR Electronic Load Instruction Reconciliation and digital NOTOC are the single source of truth across airline, ground handler and flight deck [8,9]. The Loadmaster evolves into a remote Load Control Supervisor reviewing exceptions, dangerous-goods cases and reconciliation alerts. ULDs travel on Level-4 autonomous tugs and dollies [38,39,40]. For wide-body, automated ULD handling is already standard. For narrow-body, bulk-loaded bags — historically the most injury-prone ramp task — are handled by humanoid or specialist robots [41,42,43]. Where bulk-handling robots are not yet feasible, exoskeletons [44,45] substantially reduce the injury rate as an interim measure. Power Stow Rollertrack and Tail Loader extensions [37] reach inside the hold ergonomically.	Loadmaster becomes remote Load Control Supervisor handling exceptions. Ramp baggage role mostly eliminated for bulk loading; remaining staff supervise robots and exoskeleton-equipped colleagues.	Digital W&B and ELIR end-to-end; digital NOTOC; just-in-time ULD delivery; standardised loading is validated and monitored by orchestration; 80% fewer loading errors evidenced by early ELIR adopters [9].	IATA X565/ELIR/NOTOC [8,9]; autonomous tug fleets [38,39,40]; humanoid/specialist bag-handling robots [41,42,43]; Power Stow extensions [37]; exoskeletons as bridging tech [44,45].
15	**Passenger boarding** 	Boarding is biometric, predictable and quiet. The passenger walks to the gate; cameras at the jet-bridge identify them against a one-time enrolment captured at check-in or carried via Star Alliance / SITA Smart Path interoperability. No manual boarding-pass scan. The boarding sequence is optimised dynamically by the DCS based on bag-cabin compatibility, group seating and PRM presence. PRM passengers are served by autonomous wheelchairs. At remote stands, autonomous buses deliver passengers to autonomous stairs or to a mobile-lounge concept. The Biometric Flow Supervisor handles exceptions and signs off the final passenger count through the boarding/DCS process, with the digital twin reflecting passenger flow, boarding status, PRM status, and readiness impacts.	Gate Agent becomes Biometric Flow Supervisor — exception handler, not scanner. Less stress, fewer queues, fewer disputes; automatic no-show reconciliation.	Biometric pass-through; dynamic boarding sequence; automatic passenger reconciliation; integrated PRM via autonomous wheelchair; mobile lounge or bus for remote stands.	SITA Smart Path / Star Alliance Biometrics (discontinued) / NEC I: Delight [47,58,59] (TRL 9); autonomous wheelchairs [63]; autonomous stairs [64] for remote stands; future mobile-lounge concept.
16	**Closing Doors & predeparture** 	The pre-departure walk-around is performed automatically. A stand-mounted drone or fixed camera-and-LiDAR system performs the GVI the moment cabin doors are signalled to close, flagging anomalies to the Command Centre [65–70]. Door closure is confirmed by aircraft sensors and computer vision on the bridge, not by manual hand signal. Cargo hold doors are lock-confirmed digitally. . The digital twin consolidates sensor, aircraft, bridge, cargo, and turnaround-status data to pre-populate the predeparture view. AI agents flag exceptions, and the human supervisor completes or approves the departure-ready sign-off through the appropriate operational workflow The aircraft is signed off as departure-ready via a single digital handshake. Manual walk-around is reserved for post-event inspection (lightning strike, suspected bird strike, ground damage).	Pre-departure walk-around staff role largely eliminated for routine turns; remaining staff focused on exception handling and post-event inspection.	Automated GVI replaces routine walk-around; digital door-closure verification; predeparture table auto-populated; single digital handshake replaces multi-radio sign-off.	Drone GVI [65,66,68,69,70]; stand-mounted LiDAR and CV; aircraft-side door sensors integrated into the digital twin; automated lock-indicator verification.
17	**Pushback & engine start** 	Pushback as a discrete step is largely eliminated. In the dominant scenario, a TaxiBot pulls the aircraft from gate to runway holding point with main engines off, saving 50–85% of taxi fuel on long routes [74,75]. Engine start happens immediately before take-off under ATC coordination. In the alternative scenario, on-board e-Taxi (WheelTug, Green Taxi) [79,80,81] drives the aircraft to the runway under its own power. For remaining conventional pushbacks, the tractor is electric, towbarless (Mototok, Goldhofer PHOENIX E / ATLAS 2 class) [76,77,78], controlled remotely from the Command Centre — no driver on the stand. Pushback driver shortages and 3-way comms complexity, both severe pain points today, vanish in either future scenario.	Pushback driver eliminated in the dominant scenarios; transformed into remote tractor supervisor where conventional pushback remains.	TaxiBot or on-board e-Taxi displaces pushback-plus-engine-start; engine start moved to runway hold; where conventional pushback persists it is remote-supervised and towbarless.	TaxiBot under Airbus HERON [74,75]; WheelTug nose-wheel e-Taxi [79,80]; Green Taxi main-gear e-Taxi (FAA CLEEN) [81]; Mototok / Goldhofer ATLAS 2 / PHOENIX E remote-controlled electric tractors [76,77,78].
18	**De-icing** 	De-icing remains seasonal and weather-dependent — that constraint will not disappear. But the operation becomes electrified, operator-assisted, and chemically far lighter. LIDAR-guided semi-automatic spray systems (Vestergaard OPTIM-ICE class) [88] scan the wing and tail in one pass, identify surfaces to treat, and move the nozzle through the correct pattern under operator supervision; recently extended algorithms can handle full surface treatment under good visibility. The chassis is electric (Vestergaard e-BETA, e-Mini class) [89,90], reducing emissions and cabin noise. The fluid is up to 60% recycled glycol from on-stand collection and regional treatment [91,92]. HOT tracking is automatic — the orchestration layer feeds high-resolution short-term weather data into a digital HOT timer that warns the crew if re-application is approaching [95].	De-icing operator becomes supervisor of the LIDAR-assisted spray system; less physical exposure, less time on the wing platform. Long-term, fully autonomous in good visibility.	LIDAR-assisted semi-automatic spraying; automatic HOT tracking; dynamic pad scheduling; recycled-glycol use; surface-targeted treatment reduces fluid consumption.	Vestergaard OPTIM-ICE LIDAR [88]; Vestergaard Elephant e-BETA / e-Mini electric chassis [89,90]; recycled-glycol supply [91,92]; high-resolution weather intelligence [95]; digital HOT tracker integrated with the EFB.

THE FUTURE STATE

A VISION FOR SMART RAMP

3.4 The consolidated transformation: People, Process, and Technology

The following table provides a side-by-side comparison of the transformation across the PPT framework, summarising the shift from Chapter 2 to the future vision.

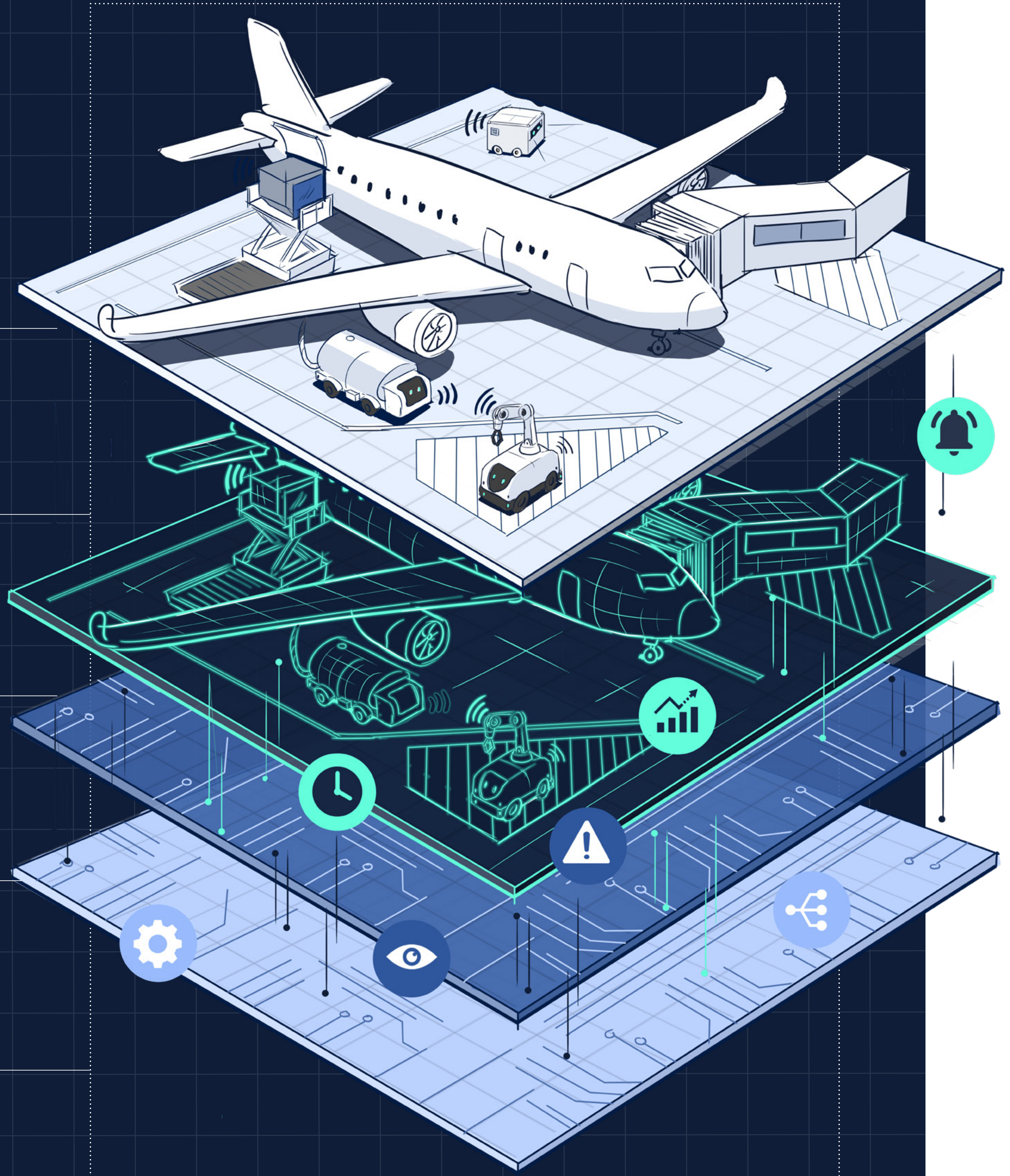
3.5 Conclusion: A new foundation for growth

The future ConOps, now extended across all eighteen IGOM-aligned steps, is not an upgrade — it is a complete architectural redesign. It replaces a foundation of manual labour, fragmented processes and ageing technology with a foundation of automation, data orchestration and elevated human oversight. **The next chapter grounds this vision in the reality of the 2025–2026 innovation landscape — vendor by vendor, step by step.**

People, Process and Technology

	Current state	Future state
People	High physical presence on the ramp across all 18 steps. Manual, labour-intensive tasks. High rates of injury and burnout — most acute in cabin cleaning, baggage handling and de-icing. Siloed roles with inconsistent training. Communication via hand signals and radio.	Remote supervision from a Command Centre. Cognitive, data-driven decision-making. Safer, indoor work environment. Multi-disciplinary roles (Turnaround Coordinator, Autonomous Vehicle Supervisor, Cabin Readiness Supervisor, Biometric Flow Supervisor). Integrated digital communication with conversational AI support.
Process	Fragmented, inconsistent procedures. Manual confirmation at every handoff. Reactive response to disruptions. Physical safety barriers (cones). Sequential, siloed steps. Paper-based fuel tickets, load sheets, NOTOCs and de-icing records.	Standardised, orchestrated workflows on IATA AHM 908 / AIDX / X565 / ELIR / NOTOC. Automated real-time status updates. Proactive predictive management. Digital geo-fencing and automated safety protocols. Integrated, parallelised processes with several steps eliminated. Biometric pass-through. Automated HOT tracking.
Technology	Legacy, non-integrated GSE. Equipment shortages. No real-time data. Paper-based logs. Vendor lock-in. Diesel GSE generating apron emissions. Manual UV-C / wet wash / manual de-icing.	Autonomous, electric, interconnected GSE across all 18 steps. Equipment-as-a-Service. Pervasive IoT sensors, CV, LiDAR. Fully digital real-time data ecosystem on a private wireless network. Open interoperable platforms and data layers. UV-C/spray cleaning robots, biometric boarding, TaxiBot/e-Taxi, LIDAR-assisted de-icing.

DIGITAL ARCHITECTURE



A VISION FOR SMART RAMP

Digital architecture

The future turnaround operating model consists of five complementary layers, each with a distinct role.

The Physical layer forms the operational foundation. This layer includes the aircraft stand and all physical assets involved in the turnaround process, such as aircraft, gates, ground support equipment (GSE), baggage systems, fuelling vehicles.

The Digital Twin serves as the live operational model and context layer. It provides a real-time and predictive representation of the turnaround operation, integrating data from the physical environment, including aircraft, stands, gates, ground support equipment (GSE), baggage flows, fuelling activities, boarding processes, safety zones, weather conditions, and operational constraints.

AI Agents form the reasoning layer. Using the Digital Twin as their source of operational context, they continuously monitor conditions, identify risks, evaluate scenarios, compare alternatives, and generate recommendations.

The Orchestration layer acts as the coordination layer. It synchronises AI agents, workflows, business rules, enterprise systems, autonomous equipment, and human decision points to ensure coordinated and controlled execution across the operation.

The Command Centre remains the human oversight and governance layer. Supervisors use operational insights and recommendations to monitor performance, approve actions where required, and intervene during disruptions or exceptional situations.

Together, these layers create a coordinated operational environment in which the Digital Twin provides situational awareness, AI Agents generate intelligence, the Orchestration Layer coordinates execution, and the Command Centre maintains human control and accountability.

THE REAL WORLD

4 INDUSTRY PROGRESS, VENDOR LANDSCAPE AND TRL

A VISION FOR INDUSTRY PROGRESS, VENDOR LANDSCAPE AND TRL SMART RAMP

4.1 Introduction:
Grounding the vision in reality

This chapter bridges the gap between the future vision and the present reality, linking the ConOps building blocks of Chapter 3 to real-world innovation across all eighteen process steps. Drawing on the nlmtd Smart Ramp Global Benchmark Research and on the Smart Ramp 2025 project portfolio, it maps the current vendor landscape, evaluates maturity using Technology Readiness Levels (TRL), and highlights the role of collaborative innovation in accelerating this transition. All projects and figures have been independently verified against primary sources (vendor and operator press releases, regulator notices, academic publications, and trade-press coverage).

The implication is clear: the highest near-term value lies in combining mature perception and software capabilities before scaling full autonomy, while using the collaborative platform to de-risk adoption and accelerate standardisation.

DEPLOYMENT	9	Actual system proven in operational environment
	8	System complete and qualified
	7	System prototype demonstration in operational environment
DEVELOPMENT	6	Technology demonstrated in relevant environment
	5	Technology validated in relevant environment
	4	Technology validated in lab
RESEARCH	3	Experimental proof of concept
	2	Technology concept formulated
	1	Basic principles observed

4.2 The state of innovation:
A reality check

Four findings emerge consistently across the inbound, on-stand and outbound phases:

1 Innovation is active, but uneven

Significant innovation is happening — especially in monitoring, perception, biometrics and assistive automation — but full end-to-end autonomy is rare. In the outbound phase, roughly 70% of named pilots cluster in just four steps (load control/loading, passenger boarding, pushback, de-icing). Catering, lavatory & water, and door-closure verification are visibly under-served.

2 Maturity varies strongly by focus area

Remote PBBs, load planning software, fixed FOD radar, turnaround monitoring, biometric boarding, digital fuelling, electric pushback tractors and electric de-icers are operationally mature (TRL 7–9). Autonomous GSE, mobile FOD robots, robotic loose-baggage handling, autonomous fuel arms and humanoid bag handlers are progressing through pilots with clear technical viability but face non-technical barriers.

3 Software is converging faster than hardware

Digital standards (IATA AHM 908, AIDX, X565, ELIR, NOTOC) [8,9], biometric platforms and AI demand-forecasting ship 12–18 months faster than equivalent GSE projects.

4 Barriers are now organisational, not technical

The key constraints are certification, safety governance, integration with legacy systems, workforce adoption, regulatory alignment (particularly biometric privacy and autonomous-GSE certification), and operating-model alignment.

THE REAL WORLD

A VISION FOR INDUSTRY PROGRESS, VENDOR LANDSCAPE AND TRL SMART RAMP

4.3 The Smart Ramp 2025 program:
Innovation in action

In its first year (March 2025 – March 2026), the program executed 19 innovation projects across 6 founding partners, 8 airports, 6 airlines and 10 technology suppliers — spanning TRL 3–9.

The collaborative model is distinctive: each partner executes their project locally with a technology provider of their choice, but all partners are involved to add requirements, perspectives and experiences. By collaborating on each other's projects, the outcomes are more relevant and applicable; development is divided across airports and runs in parallel.

The portfolio was inbound-focused by design; on-stand and outbound innovation activity catalogued in section 4.4 represents the broader industry landscape that Smart Ramp 2026 and beyond will leverage and contribute to.

4.4 Progress Along the 18 Process Steps

This section examines each step, comparing the future vision with real-world innovation. It is organised as a three-phase walk-through — Inbound (steps 1–9), On-Stand Servicing (steps 10–13), and Outbound (steps 14–18) — so that the broader operating-model picture for each phase is established before the step-by-step detail. Each phase opens with a synthesis that mirrors the per-step format used throughout: a Future Vision, a Real-World Progress narrative, and a summary table of the steps in that phase.

Partner	Project	Tech supplier	TRL
Schiphol / KLM	Autonomous 400Hz GPU Connection (Robot)	Neura Robotics	4–5
Schiphol / KLM	Autonomous FOD Detection & Removal	Avular / Roboxi	4–5
IAG	AI Turnaround Timestamping — LHR T5 (3 phases)	Assaia	9
IAG	AI Turnaround Timestamping — Seattle, Berlin, Miami	Assaia	5
IAG	Remote PBB (Auto-PBB) — London Heathrow	Dimaim	8–9
IAG	Remote PBB (Auto-PBB) — London Gatwick	Dimaim	8–9
IAG	Auto-SEGS with FOD Detection — LHR	ADB Safegate / ArgosAI	5
IAG	Auto-SEGS with FOD Detection — LGW	ADB Safegate / ArgosAI	5
ANA	Autonomous Towing Tractor for Cargo (Level 4) — Haneda	TICO / Toyota Industries	7
Miami Airport	Private 5G Network & Camera Deployment	Nokia + partners	6
Miami Airport	AI Turnaround (ramp + boarding + FOD)	ZestIOT	7–8
Miami Airport	AI Turnaround (ramp + boarding + FOD)	Lufthansa Systems ZeroG	7–8
Miami Airport	AI Turnaround (ramp + boarding + FOD)	Synaptic Aviation	7–8
MWAA	Automated Timestamping via LoRaWAN Sensor Toolkit	In-house	3
MWAA	Predictive Ramp Performance via ML	In-house	3

RESEARCH DEVELOPMENT DEPLOYMENT

THE REAL WORLD

SMART RAMP PROGRESS, VENDORS & TRL

4.4 Progress Along the 18 Process Steps

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Inbound (Steps 1–9): A Synthesis

Future Vision: The inbound phase becomes near-autonomous. Continuous FOD detection runs through fixed-asset cameras and mobile robots; the aircraft self-docks via Auto-VDGS without a marshaller; chocking and coning are replaced by digital geo-fencing or autonomous chock-bots; passenger boarding bridges dock themselves under remote supervision from the Command Centre; GPU and PCA connection is robotic; disembarkation is supported by autonomous wheelchairs, Cruz-style mobility pods and mobile-lounge concepts at remote stands; and baggage/cargo unloading is performed by humanoid robots, exoskeleton-assisted handlers and Level 4 autonomous tugs and dollies. The human role shrinks from manual execution to exception handling and supervision of the autonomous fleet.

Real-World Progress: Inbound is the most operationally diverse phase, and progress is uneven across the nine steps.

	Turnaround process step	Innovation theme	Key Vendors / Smart Ramp Projects	Notable Deployments	TRL
1	Pre-arrival	Fixed FOD detection; mobile FOD robots; pre-arrival drone GVI	ArgosAI, NCS, Xsight, Avular, Roboxi, Airtrek, Westwell; Mainblades, Donecle, Sense Aeronautics	Schiphol/KLM FOD; IAG Auto-SEGS+FOD	4 -8
2	Aircraft arrival	Automated VDGS / Auto-SEGS; drone walk-around	ADB Safegate (Safedock X), Honeywell; Mainblades, Donecle, Sense Aeronautics [69,70,71]	IAG Auto-SEGS at LHR, LGW; KLM E&M / Lufthansa Technik / Delta TechOps drone GVI	7 -8
3	GPU & PCA	Robotic GPU/PCA connection	Neura Robotics (MAiRA)	Schiphol/KLM 400Hz pilot	4 -5
4	Chocking	Ergonomic chocks; autonomous chock-bots (concept)	Aerochock, Rosen Innovation	Aerochock 40% lighter; SR2026 candidate	3-8
5	Aircraft coning	Digital geo-fencing; collision avoidance	Evitado, ADB Safegate, Airtrek Robotics	Implicit in CV/AI projects	6 -7
6	Passenger boarding bridges	Remote / autonomous PBB	TK Elevator [61], Dimaim, CIMC-Tianda [62], Adelte, Dabico, ShinMaywa, CLX Engineering, Sioux	IAG Remote PBB at LHR & LGW;; Remote PBB pilot at MUC (DIMAIM) Madrid Barajas (TKE); Lanzhou full fleet (CIMC)	4 -9
7	Open access doors	IoT seal verification; CV door status	Integrated within turnaround monitoring vendors	Part of Auto-PBB + CV/AI projects	5 -7
8	Disembarking	Autonomous wheelchairs and stairs; mobile-lounge concepts	WHILL, A&K Robotics (Cruz pods) [63], Mallaghan [64]	YVR Cruz pod trial; SR2026 candidate	5 -7
9	Unloading bags & cargo	Robotic bag handling; exoskeletons; autonomous tugs/ULDs	Aurrigo [38], TractEasy/EasyMile, Oxa [40], Toyota Industries, AAT (ABLE) [42], Journey Robotics, SARCOS, Dexterity, JAL/Unitree; German Bionic, Ottobock	ANA L4 cargo tractor; Schiphol Aurrigo + AAT ABLE; LHR Oxa+DHL; CVG Aurrigo TractEasy at Munich (pilot)	5 -8

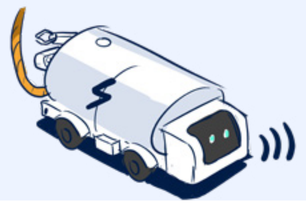
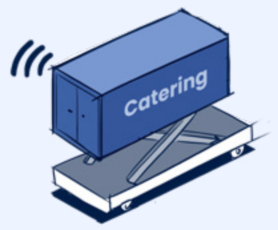
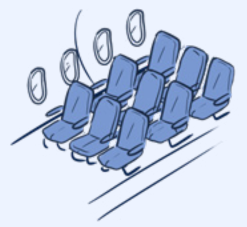
THE REAL WORLD

A VISION FOR INDUSTRY PROGRESS, VENDOR LANDSCAPE AND TRL SMART RAMP

On-stand servicing (Steps 10 - 13):
A Synthesis

Future Vision:

On-stand servicing concentrates four parallel workflows — fuel, catering, cabin cleaning, and lavatory/water — within a small physical footprint and a tight time window. The future vision is electrified, single-operator equipment with smart hydraulics; AI-driven demand forecasting (especially for catering and water); IoT-triggered condition-based servicing of lavatories and potable water; robotic docking of service interfaces; full automation of repeatable tasks (UV-C disinfection, antimicrobial spraying, surface cleaning); and SAF-aware fuel-handling tied to airline carbon-accounting platforms via the IATA CADO registry.

	Turnaround process step	Innovation theme	Key Vendors / Smart Ramp Projects	Notable Deployments	TRL
10	**Fuelling** 	Autonomous refuellers; digital ITP; SAF integration; smart hydrants	Skytanking/Stuttgart [11], Titan Aero/Kerry [12], VINCI/WFS/Neste [13], i6 Group Fusion6 [14], IATA CADO [10], Air Liquide/ADP [15]	Schiphol/KLM FOD; IAG Auto-SEGS+FOD	7 -9
11	**Catering** 	Single-operator electric trucks; AI demand forecasting	Aviogei [16], Miles GSE [17], Mallaghan CT6000E [18], dnata electrification program [19], KLM Catering Services [20], Kickstart AI/TRAYS [21], Lumitics Ditto [22]	KLM Schiphol electric fleet; Mallaghan/dnata Prague trial; KLM TRAYS 63% food-waste reduction	7 -9
12	**Cabin cleaning & preparation** 	UV-C disinfection; antimicrobial spray; shared cabin/terminal cobot fleets	Aero HygenX RAY [23,24], NovaRover/Zoono [25], Aerowash [26], TASKI/Diversey [28], Gaussian Robotics [29], SoftBank/Brain Corp [30], OhmniClean/Symbotic [31], Hivebotics [32], Unitree [33]	Avelo, Ravn Alaska, United; HKIA, Zurich, Munich, ~100 cobots / 10 US airports; Emirates trial	7 -9
13	**Toilet & water** 	Smart-lavatory IoT (concept); electrified service trucks; robotic docking (concept)	Mallaghan electric toilet trucks [34]; Vestergaard, Cartoo, Miles, Tianyi, ORIENTITAN; open-architecture IoT publications	No fleet-wide IoT yet; SR2026 lead pilot candidate	3-7

A VISION FOR INDUSTRY PROGRESS, VENDOR LANDSCAPE AND TRL SMART RAMP

Outbound (Steps 15 – 18):
A Synthesis

Future Vision:

Outbound is where the turnaround "exits" — load close-out, passenger boarding, doors closed, pushback, engine start and (in winter) de-icing.

The future vision is highly digital: software-driven load planning with ELIR-compliant electronic load instructions and digital W&B (X565); biometric pass-through boarding with self-boarding gates and dynamic boarding sequencing; sensor- or computer-vision-confirmed door closure feeding straight into A-CDM; engine-out / single-engine taxi-out routinely supported by hybrid-electric TaxiBots and, in the longer term, fully-electric on-aircraft taxi systems; and semi-automatic moving toward fully autonomous de-icing with LIDAR-assisted nozzle placement, recycled glycol and AI runway-condition prediction.

	Turnaround process step	Innovation theme	Key Vendors / Smart Ramp Projects	Notable Deployments	TRL
14	**Load control & loading**	Digital W&B / ELIR; load-planning software; autonomous baggage tugs; robotic bag handling; exoskeletons	IATA X565/ELIR [8,9], Wiremind SkyPallet [35], Etihad/Speedcargo [36], Power Stow [37], Aurrigo [38], EasyMile [39], Oxa [40], Journey Robotics [41], AAT ABLE [42], SARCOS [43], German Bionic [44], Ottobock [45], Schiphol BOOST [46]	SkyPallet 1,200+ users; Aurrigo at Schiphol/KLM, CVG, UPS EMA; Oxa+DHL LHR 1,300 km; PIT autonomous bag tug	5 -9
15	**Passenger boarding**	Biometric pass-through; autonomous PBB; mobility pods for PRM	SITA Smart Path [47], MIA SITA EPP [48], DigiYatra [49], TSA [51], SEA/ Thales/Dormakaba [52], Abu Dhabi Zayed [53], NEC Face Express [54], Alaska Touchless ID [55], CBP/iProov [56], Heathrow [57], Incheon Smart Pass [58], TK Elevator [61], CIMC [62], A&K Robotics Cruz [63], Mallaghan [64]	KLM Schiphol electric fleet; 45+ airports SITA Smart Path; MIA largest US EPP (Nov 2025); Incheon 158 gates; Lanzhou full autonomous PBBs Mallaghan/dnata Prague trial; KLM TRAYS 63% food-waste reduction	6 -9
16	**Closing doors & predeparture**	Drone GVI; CV door verification; AI turnaround orchestration	Delta TechOps [65], Jet Aviation [66], Emirates/Near Earth [68], Donecle [69], Mainblades [70], IAG/Sense [71], Lufthansa/Fraport zeroG [72], Heathrow/IAG/Assaia [73], Indra/ Synaptic [74]	LHR 116 gates Assaia (£2.3bn program); FRA 20 stands "seer"; SR2026 candidate (sensor door close)	5 -8
17	**Pushback & engine start**	Hybrid-electric TaxiBots; electric pushback tugs; engine-out taxi-out; hydrogen tow tractors	SESAR/Airbus HERON [75], KLM/ Schiphol TaxiBot [76], Mototok [77,78], Goldhofer [79], WheelTug [80,81], Green Taxi Aerospace [82], KLM Goldhofer fleet [84,85], Brussels/DHL/ Mulag [86], Schiphol/Ballard TULIPS [87], Cranfield/Exeter hydrogen [88], OpenAirlines SkyBreathe [89]	KLM first commercial TaxiBot flight (10 Dec 2024); LHR T5A 28 Mototoks; Munich 14 PHOENIX E; UK first hydrogen turn at Exeter	5-9
18	**De-icing**	LIDAR-assisted semi-automatic de-icing; electric de-icers; recycled glycol; AI runway-condition prediction	Vestergaard OPTIM-ICE [90], Vestergaard e-BETA Oslo / production [91,92], Clariant Safewing [93], Finavia [94], BCG/Avinor [95], Aalto/Finavia [96], Tomorrow.io [97]	Vestergaard Lisbon GSE Expo Sept 2024; Avinor 43 airports AI; Helsinki recycled glycol since Nov 2023	6-9

A VISION FOR INDUSTRY PROGRESS, VENDOR LANDSCAPE AND TRL SMART RAMP

4.5 The Command Centre:
Operational intelligence and orchestration software

The future ConOps envisions a remote Command Centre using a digital twin and AI-powered orchestration. The stack is maturing rapidly across three converging layers.

Turnaround Monitoring (TRL 7–9):

Using cameras and AI to automatically detect and timestamp key turnaround events is one of the most mature outbound capabilities. Assaia and Schiphol Airport Deep Turnaround are a dominant players — the Heathrow + IAG + Assaia ApronAI rollout (announced Jul 2025) extends to 116 gates across T2/T3/T5 with 540+ cameras as part of a £2.3bn investment [73]. The Lufthansa + Fraport + zeroG "seer" rollout reached 20 stands at Frankfurt by Q3 2025 [72]. Indra and Synaptic Aviation deployed AI video analytics at Madrid Barajas, Barcelona El Prat and Palma de Mallorca in Mar 2026 [74]. At MIA, the Smart Ramp program tests three competing vendors — ZestIOT, Synaptic Aviation, and Lufthansa Systems ZeroG — in a unique comparative pilot. MWAA develops in-house sensor-based timestamping and ML predictive ramp performance.

Resource Management (TRL 7–8):

Software to manage and optimise day-to-day ramp operations — planning and tracking turnaround tasks, allocating staff and GSE, monitoring SLAs. Key vendors: Assaia, Zafire (FirstRamp), Cohelion, EMU Analytics, OTSi, and INFORM GroundStar (in production at Frankfurt and Heathrow).

Integrated Orchestration (TRL 6–7):

The ultimate goal — and the direct precursor to the future Command Centre — is to connect AODB, A-CDM, monitoring, perception and analytics into a single operational picture with predictive and exception-based decision-making. This is the least mature but most critical category. Vendors include Avtura, Emma, Smarter Airports, Airport Labs and Aeroficial Intelligence. Oshkosh Corporation demonstrated a prototype turnaround-optimisation robot at CES 2025/2026 designed to coordinate ground crew tasks from arrival to pushback [100].

Software layer	Key vendors	Notable Deployments	TRL
Turnaround Monitoring (CV/AI Timestamping)	Assaia [73], ZestIOT, Synaptic Aviation [74], Lufthansa Systems ZeroG [72], Tarmac, Intell-act, Deep Turnaround, Unleash, Matroid, Indra	IAG/LHR Assaia 116 gates; MIA 3-vendor pilot; Frankfurt seer; Madrid Indra, Schiphol Airport, Munich: assaia	7–9
Resource Management	Assaia, Zafire (FirstRamp), Cohelion, EMU Analytics, OTSi, INFORM GroundStar	Frankfurt, Heathrow (INFORM)	7–8
Integrated Orchestration	Avtura, Emma, Smarter Airports, Airport Labs, Aeroficial Intelligence; Oshkosh prototype [100]	Smart Ramp 2026 focus area; Smarter Airports' Airheart platform in implementation in Munich	6–7

SMART RAMP PROGRESS, VENDORS & TRL

4.6 Enabling Infrastructure:
Connectivity and data

The future ConOps depends on a robust data and connectivity infrastructure. Miami International Airport leads within Smart Ramp, deploying a private 5G network with Nokia. Purdue University Airport deployed an Ericsson + Saab private 5G CBRS network from 2024 supporting flight coordination, drone detection and autonomous ground equipment — with reported 30% productivity gains [96].

Dallas-Fort Worth (DFW) deployed an AT&T private 5G network from 2023 with over 200 access points supporting asset tracking [97]. San Sebastián Airport (Aena) deployed a Cellnex + Nokia private 5G pilot from June 2023 for drone-based environmental monitoring [98]. Tomorrow.io provides high-resolution short-term weather forecasts integrated into orchestration layers across many winter hubs [95].

On data standards, adoption of IATA AHM 908, AIDX, X565, ELIR and digital NOTOC is the single highest-multiplier intervention in the outbound chain [8,9].

4.7 Consolidated Vendor Landscape

Step / layer	Dominant vendors / platforms	TRL
1 — Pre-Arrival & FOD	ArgosAI, NCS, Xsight, Avular, Roboxi, Mainblades, Donecle	TRL 4–8
2 — Aircraft Arrival & VDGS	ADB Safegate, Honeywell, Mainblades, Donecle, Sense Aeronautics	TRL 7–9
3 — GPU & PCA	Neura Robotics; (future PBB-integrated GPU/PCA)	TRL 4–5
4 — Chocking	Aerochock, Rosen Innovation; (autonomous chock-bot concept)	TRL 3–8
5 — Aircraft Coning	Evitado, ADB Safegate; digital geo-fencing software	TRL 6–7
6 — Passenger Boarding Bridges	TK Elevator, Dimaim, CIMC-Tianda, Adelte, Dabico, ShinMaywa, CLX Engineering	TRL 4–9
7–8 — Open Doors & Disembarking	WHILL, A&K Robotics, Mallaghan	TRL 5–8
9 — Unloading Bags & Cargo	Aurrigo, TractEasy, Oxa, Toyota Industries, AAT, Journey Robotics, SARCOS, Dexterity, German Bionic, Ottobock	TRL 5–8
10 — Fuelling	Skytanking, Titan Aero, i6 Group, Skymetrix, Shell Aviation, Rampmaster, IATA CADO	TRL 5–9
11 — Catering Servicing	Aviogei, Miles GSE, Mallaghan, dnata, Kickstart AI (TRAYS)	TRL 7–9
12 — Cabin Cleaning & Preparation	Aero HygenX, OhmniClean/Symbotic, NovaRover/Zoono, TASKI/Diversey, Gaussian Robotics, Flagship/SoftBank, Hivebotics	TRL 6–9
13 — Toilet & Water Servicing	Vestergaard, Mallaghan, Cartoo, Miles, Tianyi, ORIENTITAN	TRL 5–9
14 — Load Control & Loading	IATA X565/ELIR/NOTOC, Wiremind, Speedcargo, Cargo-Planner, Power Stow, Aurrigo, TractEasy, Oxa, Journey Robotics, AAT, German Bionic, Ottobock, BEUMER, Vanderlande, Daifuku	TRL 5–9
15 — Passenger Boarding	SITA (Smart Path) on NEC, Star Alliance Biometrics, SEA/Thales/Dormakaba, Aware+iProov, Mallaghan, TK Elevator, CIMC, A&K Robotics	TRL 5–9
16 — Closing Doors & Predeparture	Mainblades, Donecle, Sense Aeronautics, Near Earth Autonomy; Assaia, ZeroG, Indra/Synaptic	TRL 3–9
17 — Pushback & Engine Start	TaxiBot (IAI/TLD), Mototok, Goldhofer, WheelTug, Green Taxi, OpenAirlines, INFORM	TRL 5–9
18 — De-icing	Vestergaard, Clariant, Finavia, Tomorrow.io, BCG+Avinor	TRL 5–9
Monitoring & Orchestration	Assaia, Deepturn ZestIOT, Synaptic, Lufthansa Systems ZeroG, Tarmac, Indra, INFORM, Avtura, Emma, Smarter Airports, Airport Labs, Aeroficial	TRL 6–9
Connectivity & Data	Nokia, Ericsson + Saab, AT&T, Cellnex; IATA AHM 908/AIDX/X565/ELIR/NOTOC; Tomorrow.io	TRL 6–9
Cross-Cutting Programs	UK Airside Automation Group (formed Sep 2025) [99]; IATA Enhanced GSE Recognition Program (mandatory at ISAGO locations from Apr 2025) [9]; BOOST baggage coalition [46]	Industry-wide

A VISION FOR INDUSTRY PROGRESS, VENDOR LANDSCAPE AND TRL SMART RAMP

4.8 Conclusion:
The bridge between vision and reality

The 2023–2026 period has been a definitive shift in ramp operations — **from isolated, manual tasks to the early formation of integrated, autonomous, zero-emission ecosystems.**

The same pattern recurs across the eighteen steps: software has overtaken hardware, mature solutions exist for most categories where the operation bleeds time and cost, and the binding constraint is no longer invention but adoption.

The implication for Smart Ramp 2026 is sharp. The strongest near-term value lies in (a) co-piloting the digital standards that act as multipliers (X565, ELIR, NOTOC, AHM 908, AIDX); (b) shared validation of the autonomous-baggage and electric-pushback platforms that already have an operational track record; and (c) focused exploratory work on the two steps where industry innovation is currently thinnest — lavatory & water servicing (Step 13) and door-closure verification (Step 16).

5 CONCLUSION AND NEXT STEPS

SMART RAMP CONOPS: THE FUTURE OF AIRCRAFT TURNAROUND

5.1 Conclusion:
A complete ConOps for the aircraft turnaround

This whitepaper has, for the first time, articulated a complete Concept of Operations for the aircraft turnaround across all eighteen IATA Ground Operations Manual-aligned process steps. It is the consolidated product of the Smart Ramp 2025 and 2026 programs, four co-design workshops covering inbound and on-stand/outbound, and ongoing dialogue with nine partner organisations spanning Europe, North America and Asia-Pacific. Stands as the consortium's definitive view of where ramp operations are heading over the next decade.

Technology is no longer the constraint

Across all 18 process steps, mature solutions exist at TRL 7–9 in the categories where ramp operations bleed the most time and money. The bottlenecks are organisational — certification, integration with legacy systems, workforce adoption, regulatory alignment. The Smart Ramp program was designed precisely to address these bottlenecks through collaborative validation and shared evidence.

Software has outrun hardware.

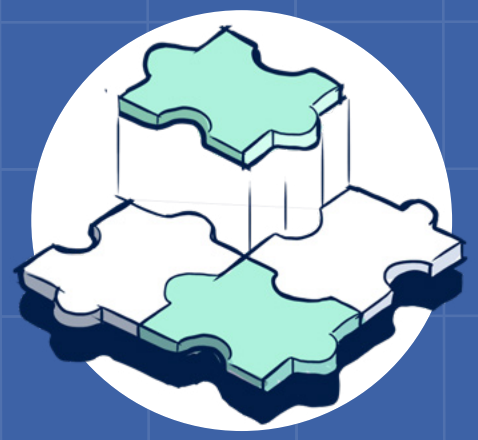
Digital standards (IATA X565, ELIR, NOTOC, AHM 908, AIDX) [8,9], AI turnaround timestamping [72,73,74], biometric pass-through [47,51,60], AI demand forecasting [21] and engine-out taxi software [89] offer near-term, high-confidence gains and ship 12–18 months faster than equivalent GSE projects. They are the bridge that lets airports and airlines start capturing the future ConOps value today, rather than waiting for autonomous fleets to certify.

Two steps remain under-served by innovation

Toilet & Water Servicing (step 13) and Closing Doors & Predeparture (step 16) lag substantially behind the rest of the turnaround. Both are good candidates for focused Smart Ramp 2026 pilots, where the consortium can act as a neutral validation platform and establish a shared evidence base where none currently exists.

The business case is far larger than headcount reduction.

- Operational resilience (preventing knock-on delays at ~$100 per minute)
- Safety risk reduction (~$10B per year in industry ground damage) [4],
- Sustainability (fuel savings of 50–85% via TaxiBot [75]
- ~5% airline-wide via EOTI/SETO [89]
- Glycol reductions via LIDAR-assisted de-icing [88]
- Food-waste reductions of 60%+ via AI forecasting [21])
- Collectively dwarf direct labour savings, Provide solutions for large demographic changes in the workforce.
  Framing automation as workforce augmentation — not replacement — has been the single biggest adoption lever in the 2025 program.



Standards and interoperability are the multiplier

Up to 80% of innovation project time is currently spent building custom integrations. Adoption of IATA AHM 908, AIDX, X565, ELIR, NOTOC [8,9] and a shared FOD library is the pre-condition for everything else to scale. The consortium's investment in these standards is the single highest-leverage activity available to it in 2026.

5.2 Standards and interoperability are the multiplier

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5.3 A strategic roadmap:
Three Horizons

Achieving the future CONOPS requires a structured, multi-layered approach across three parallel strategic themes. Progress in all three is necessary and mutually reinforcing.

Themes	Horizon 1: Now (0–3 Years)	Horizon 2: Next (3–7 Years)	Horizon 3: Future (7–10+ Years)
Data & connectivity	Scale AI turnaround monitoring for full visibility. Deploy private 5G networks.	Federate data into unified layer. Develop Digital Twin v1.0 for situational awareness.	AI-powered orchestration layer for predictive decision-making. Mature Digital Twin v2.0.
Automation & robotics	Scale remote/ autonomous PBBs. Expand autonomous GSE pilots. Deploy exoskeletons.	Widespread autonomous tractors. Mobile FOD robots. Robotic arms for baggage handling.	Humanoid robots for complex tasks. Multi-functional robotic platforms. Full fleet autonomy.
Operating model & roles	Centralise PBB and monitoring functions. Launch reskilling programs.	Formalise multi-stakeholder Command Centre. Define Turnaround Coordinator and Disruption Team roles.	Fully integrated orchestration hub. Establish the "Service Provider" ownership model.

5.4 Prioritisation:
Where to focus first

Resources are finite. Prioritisation must be driven by targeting the most severe bottlenecks from Chapter 2 with the most mature and feasible solutions from Chapter 4.

Achieving the future CONOPS requires a structured, multi-layered approach across three parallel strategic themes. Progress in all three is necessary and mutually reinforcing.

Priority	Focus Area	Rationale	Key Technologies
High impact **High feasibility**	Achieve total situational awareness	Addresses the core bottleneck of poor communication and data silos. Provides the foundational data layer for all future automation.	AI Turnaround Monitoring, Sensor Timestamping, 5G Connectivity, Remote PBB's.
High impact **Medium feasibility**	Automate high-strain vehicle movements	Directly tackles workforce strain, scarcity, and safety risks. Reduces aircraft ground damage.	Autonomous Baggage/Cargo Tractors, Mobile FOD Robots, Exoskeletons
High impact **Low feasibility**	Solve complex robotic manipulation	Eliminates the most physically demanding and injury-prone manual tasks. Represents the final frontier.	Robotic Loose Baggage Handling, Robotic GPU Connection, Autonomous Chocking

By focusing first on achieving complete operational visibility, the industry creates the data-rich environment necessary to safely and effectively manage the subsequent waves of physical automation.

CONCLUSION AND NEXT STEPS

5.5 The critical conversations that must begin now

The greatest barriers to the future CONOPS are no longer technical—they are organisational, regulatory, and cultural. The vision is a catalyst for a series of critical conversations that must start immediately, involving a broader set of stakeholders than ever before.

1 Redefining Roles and Responsibilities

The greatest barriers to the future CONOPS are no longer technical—they are organisational, regulatory, and cultural. The future operating model introduces new roles—Turnaround Coordinator, Disruption Team, Autonomous Vehicle Supervisor—while transforming or eliminating others. The workshop deliberately defined these roles without assigning them to specific organisations, because this is a conversation the industry must have collectively. Who operates the Command Centre? Who owns and maintains the autonomous fleet—does every handler have their own, or does a neutral "Service Provider" lease equipment as a service? How are responsibilities and costs shared in this deeply interconnected ecosystem? These questions must be addressed through structured dialogue between airports, airlines, ground handlers, and regulators. n is a catalyst for a series of critical conversations that must start immediately, involving a broader set of stakeholders than ever before.

> The current workforce must be involved in defining the skills, training, and career paths for the jobs of the future
>
> SMART RAMP CONSORTIUM — CALL TO ACTION

2 Evolving Standards and Legal Frameworks

The current rulebook was not written for an autonomous ramp. A multi-stakeholder dialogue is urgently needed across two dimensions. First, industry standards bodies (IATA, ACI, ICAO) must develop new standards for data interoperability between orchestration platforms, safety validation of AI algorithms, and operational certification of autonomous GSE. The IATA Ground Operations Manual (IGOM) will need a significant update to reflect the new CONOPS. Second, aviation regulators (EASA, FAA) and insurers must establish clear legal frameworks covering certification pathways for autonomous systems, liability models in the event of incidents involving robots, and the application of data privacy laws such as GDPR to ramp operations involving pervasive camera and sensor monitoring.

3 Engaging the Workforce and Unions

The transition to a Smart Ramp must be a "just transition." This requires proactive and transparent engagement with employee representatives and unions to co-design new roles, develop robust reskilling programs, and champion a culture of safety and collaboration. The current workforce must be involved in defining the skills, training, and career paths for the jobs of the future.

5.6 A call to action

The vision for the Smart Ramp is clear, and the roadmap is taking shape. The Smart Ramp Program, as a neutral and collaborative platform, provides the ideal forum to host these critical conversations and to continue de-risking innovation through shared projects and evidence-based learning. The time for isolated experiments is over. The next step is for the industry—airports, airlines, handlers, regulators, and technology providers—to come together to build this future, one collaborative project at a time. The On-Stand and Outbound phases of this whitepaper series, due in March 2026, will extend this vision to the full turnaround cycle, completing the picture of the Smart Ramp of the future.

> **"The technology is ready.** The next decade is about adoption, integration and standards — and that is collaborative work, not a single-organisation undertaking."
>
> SMART RAMP CONSORTIUM

APPENDIX

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APPENDIX

This appendix lists external sources cited in the whitepaper. Citations are inline as [n] in Vancouver style, with each number referring to a unique source that may be reused throughout the document. Statements and conclusions arising from the Smart Ramp 2025 program, the two co-design workshops, or partner organisations are not separately cited.

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APPENDIX

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The future is not built alone, but together, through alignment, integration and shared direction.

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