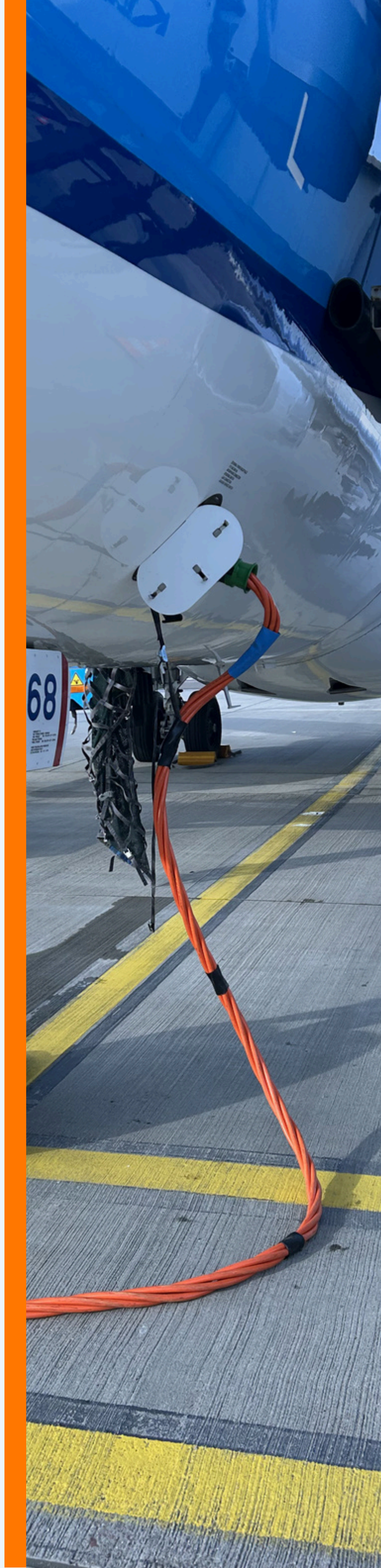
Making the Connection

Conceptualising autonomous aircraft ground power connection at Schiphol Airport through an adaptive roadmap



Master Thesis | Strategic Product Design
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Making the Connection - *Conceptualising autonomous aircraft ground power connection at Schiphol Airport through an adaptive roadmap*

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Chapter opening images from Royal Schiphol Group.

Preface

I am proud to present this thesis as the final project of my Master's in Strategic Product Design at TU Delft. I began this master's as an inexperienced student, and looking back now, I can see how much I have learned and grown along the way, both from my studies and as a person, leaving ready to step into working life with much more to draw on than when I started.

I chose this project because the scale and complexity of Schiphol have always interested me. Getting to graduate inside such a complex and impactful organisation was something I am grateful for, and even the small understanding of that complexity I now have will change how I look at the operation.

The project was both interesting and difficult. Designing a concept for a future this far off, while weighing it against the current situation and expected developments, was harder than I had thought. I learned a lot from being part of a team at Schiphol. Seeing how the working world operates, and how projects there take shape, was insightful and a real inspiration for this work.

This project felt like the real close of my master's. It was a final challenge to apply everything I had learned independently and at a larger scale than before. It came with ups and downs, from real pride when things came together to harder moments when the direction was unclear and I doubted whether I was on the right track.

I would like to sincerely thank Sicco Santema and Garoa Gomez Beldarrain for their guidance and honest feedback. You were always there to help, and your sharp, critical feedback pushed this project a step further each time. I also want to thank Rosina Kotey for your operational knowledge and critical questions, which pushed my thinking and helped shape this result.

I would also like to thank the whole team at the Innovation Hub for making me feel welcome from the start and for always being willing to help. I am also grateful to everyone at Schiphol, KLM, and Swissport who took part in my co-creation sessions and took me airside, for your time and openness.

Finally, I am grateful to my friends, my boyfriend, my brother, and my parents for their support, encouragement, and confidence throughout this project and my studies. It meant more than I probably showed at the time.

Enjoy reading!

Maaike Krap

MKrap

Abstract

Airports increasingly turn to automation to improve efficiency and reduce emissions, yet a gap often remains between proving a system works and integrating it into daily operations. At Amsterdam Airport Schiphol, the autonomous 400 Hz ground power connection, which allows an aircraft to switch off its engines/APU after arrival, illustrates this gap: a Proof of Technology showed it can be performed autonomously, but not how it should be integrated into the inbound operation.

This thesis treats that integration not as a technical problem but as a socio-technical one, focusing on the divergence between Schiphol, as infrastructure provider, and the ground handlers, as operational users. Mapping the current operation and analysing where their interests pull apart revealed five tensions, each a point where positioning the system was not enough and an explicit design choice was needed. Resolving these in co-design produced shared choices on deployment, autonomy and role division, co-development, safe behaviour, and digital integration.

To hold these choices together under an uncertain future, they were synthesised using an Adaptive North Star: a direction deliberately kept open to change rather than a fixed endpoint. This direction was made concrete through three artefacts: a Horizon 3 operational concept, a horizon-based roadmap organised around learning milestones, and a phased set of requirements.

The thesis contributes an approach for moving autonomous airside systems from technical feasibility towards operational integration, built around the operation a system enters rather than only the task it performs. For Schiphol, it provides a grounded basis for further pilots and decisions.

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Abbreviations

ACI – Airports Council International
AI – Artificial Intelligence
APU – Auxiliary Power Unit
CDM – Collaborative Decision Making
DME – Diesel Motor Emissions
e-GPU – Electric Ground Power Unit (mobile)
EPA – Equipment Parking Area
ERA – Equipment Restraint Area
ESA – Equipment Staging Area
FOD – Foreign Object Debris
FPU – Fixed Power Unit
GPU – Ground Power Unit
GSE – Ground Support Equipment
HRT – Human-Robot Teaming
IATA – International Air Transport Association
IEM – Impact–Effort Matrix
LORA – Levels of Robot Automation
MLP – Multi-Level Perspective
MoSCoW – Must, Should, Could, Won't
NaBo – Narrow-Body aircraft
NPA – No Parking Area
OTISS – Orchestrating Traffic Information System Schiphol
PBB – Passenger Boarding Bridge
PoT – Proof of Technology
ROS – Ramp Orchestration System
RRI – Ramp Readiness Indicator
SIF – Seamless Inbound Flow
STS – Socio-Technical Systems
UFP – Ultrafine Particles
VDGS – Visual Docking Guidance System
VDME – Vehicle and Diesel Motor Emissions
VME – Vehicle Motor Emissions
VOP – Vliegtuigopstelplaats / aircraft stand position
WiBo – Wide-Body aircraft

Chapter 1 | Project Introduction

This chapter introduces the project: the pressures driving airport automation, Schiphol's autonomous airside ambition, and the gap this research addresses. It sets out the scope, problem definition, and research questions that guide the thesis.

1. Project Introduction

1.1. Pressures on the aviation sector

The aviation industry is undergoing a major digital transformation, driven by developments in data, artificial intelligence, and automation [14, 16, 21, 32]. Airports are increasingly adopting these technologies in response to a changing operational context. Stricter environmental and safety regulations, labour shortages, and rising passenger volumes are placing airports under pressure to improve their efficiency, resilience, and sustainability [68].

This pressure is expected to increase in the coming decades. Airports Council International (ACI) World forecasts that global passenger numbers will nearly double by 2045, reaching 18.8 billion passengers [3].

As passenger volumes grow, so does the environmental footprint of aviation. The sector currently accounts for approximately 2–4% of global carbon dioxide emissions [1], and faces increasing regulatory and societal pressure to reduce this impact [39]. Airports are therefore required to pursue operational growth and environmental improvement simultaneously, a tension that shapes much of the strategic context for this project. This project is situated at Amsterdam Airport, part of Royal Schiphol Group, which operates under these combined pressures.

1.2. Schiphol Airport strategy

In response to these sector-wide pressures, Royal Schiphol Group has formulated strategic ambitions that focus on maintaining connectivity while improving environmental and operational performance. In its strategic plan for 2025–2035, Schiphol identifies several directions that relate to the challenges described before, including preparing for passenger growth, creating a healthy and safe working environment, and reducing dependency on manual tasks through technology [76].

These strategic directions build on Schiphol's long-term vision. Within this vision, Schiphol aims to become a waste- and emission-free airport by 2030 and to transition towards fully autonomous airport operations by 2050 [72, 68]. This is reflected in the Autonomous Airside Operations programme [66], part of the Seamless Inbound Flow (SIF) initiative, which provides the broader context for this project.

1.3. Challenges of integration of automation in organisations

The integration of automation, to replace manual processes, is a widespread phenomenon across industries [11, 27, 45, 52]. Yet despite this growing demand, automation innovation often involves challenging, complex, and long processes, while many projects ultimately see poor implementation in practice [38, 19, 51]. Automation and AI are often framed as quick fixes for organisational challenges [17, 50].

Schiphol faces these same challenges. While the long-term autonomous airside vision is clearly defined, translating it into concepts that fit the operational context, align with organisational strategy, and support the needs of those who work with the technology remains a significant challenge. Automation integration is therefore not only a technical problem, but an operational design problem and one that requires a structured approach to bridge the gap between strategic ambition and operational reality, the aim of this research.

1.4. Scope: the inbound ground power process

Aircraft handling consists of a wide range of interdependent tasks, stakeholders, and operational dependencies, together referred to as the turnaround process. Within this broader process, this project focuses on the automation of the 400 Hz connection: the process in which an aircraft is connected to external ground power, allowing the aircraft to shut down its engines and/or Auxiliary Power Unit (APU).

To support the Seamless Inbound Flow initiative, the project specifically focuses on the inbound phase up to engine shutdown, as shown in orange in Figure 1.1.

An initial Proof of Technology demonstrated that a robotic system can navigate to the aircraft stand, detect and open the access panel, and insert the 400 Hz connector autonomously [55]. Since technical feasibility can be assumed, this research focuses on the operational question: how an autonomous 400 Hz connection system should be integrated within Schiphol's inbound airside operation.

The autonomous 400 Hz connection involves a wide range of stakeholders. This research focuses specifically on Schiphol and ground handlers: Schiphol as the infrastructure provider and ground handlers as its primary users. The perspectives of the broader stakeholder field are acknowledged but fall outside the scope of this research.

1.5. Problem Definition

How the autonomous system should be integrated within the inbound operation is not yet defined. Schiphol's Autonomous Airside Operations programme sets a long-term vision for autonomous airside operations, and the Proof of Technology has shown that the physical connection task can be automated. What lies between the two remains open: the programme defines neither which operational concept should bridge the current 400 Hz process and the autonomous future, nor which development steps are needed to move towards it.

This is not unique to Schiphol; it reflects a broader challenge in automation integration. Prior work shows that automation often struggles to move from technical demonstration to everyday operational use, especially in complex organisational environments where technologies must fit existing practices, stakeholder responsibilities, and changing work routines [19, 38, 13]. Research on automation integration and socio-technical systems further shows that successful automation depends on appropriate task allocation, clear role division and trust between human workers, and automated systems [57, 48]. These studies provide important principles for what automation should account for, but offer less guidance on how such principles should be translated into concrete, workflow-level design choices for a specific operational process.

In the 400 Hz case, this translation is the central unresolved problem. The connection is technically feasible, but it is not known how the autonomous system should be operationally positioned within the inbound flow. The challenge addressed in this research is therefore to develop an operational concept for autonomous 400 Hz connection that is grounded in Schiphol's airside operation and translates technical feasibility into workflow-level design choices and a phased development path.

1.6. Research Questions

Based on the scope and problem definition, the main research question for this project has been formulated as follows:

What operational concept and development path enable the integration of an autonomous 400 Hz connection into Schiphol's aircraft arrival operation?

To answer this main research question, five subquestions are formulated:

- **RQ1:** How is the 400 Hz connection currently organised within Schiphol's inbound operation, and what challenges occur?
- **RQ2:** What makes an autonomous connection valuable in the operation, and what makes it difficult to integrate?
- **RQ3:** Where do the interests of Schiphol and the ground handlers diverge in what the autonomous connection should achieve?
- **RQ4:** What design choices resolve these tensions into an operational concept?
- **RQ5:** How can this concept be integrated into Schiphol's inbound airside operation?

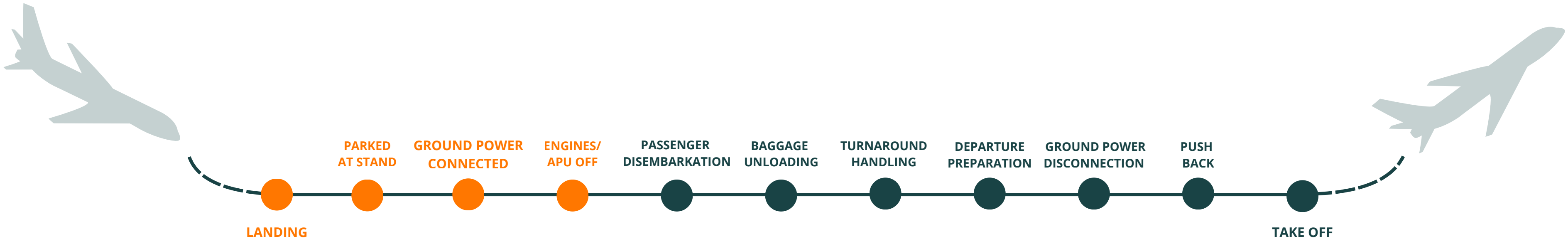

Figure 1.1: The aircraft turnaround process, with the inbound phase up to engine shutdown highlighted in orange as the scope of this project

1.7. Project Approach

This research develops an operational concept for the autonomous 400 Hz connection in three connected artefacts: a directional concept for Horizon 3, a horizon-based roadmap towards it, and a phased set of operational requirements. Together, these artefacts deliberately do not present a fixed end state, but a phased development logic and directional concept that clarify what must be learned, validated, and organised before autonomous 400 Hz connection can be responsibly integrated into Schiphol's inbound airside operation. The approach below is framed around why each step was needed to reach the operational concept, the approach is visualised in Figure 1.2.

Because the technology already works while its operational concept does not [55], and because automation often fails when it does not fit the operation [38, 90], the approach starts from the current operation. By combining principles from literature with an analysis of the current workflow, this research defines a set of design considerations. These cannot all be addressed at once, so prioritising them with both parties sets the focus on workflow positioning: how the system fits the existing sequence of dependencies.

Positioning it in the workflow raises two questions, what value it adds and what makes it hard to integrate, which structure the analysis into drivers and barriers. Where the two pull in opposite directions and Schiphol and the ground handlers would resolve that pull differently, a tension emerges: a point where a design choice is needed [91, 89]. Because these choices affect daily work practices, responsibilities and operational feasibility, they require input from both Schiphol and ground handlers, so a co-creation session brought them together to resolve them.

These choices still need one direction, yet the future operation cannot be predicted. The research therefore sets the direction through an Adaptive North Star: a strategy that takes the conventional North Star [5] but makes it deliberately contradictory: where a North Star normally provides a fixed point of certainty, this one embraces openness, holding the choices together while keeping explicit what still has to be validated. This opens a new perspective: because the direction also states what remains open, committing to it becomes a lighter choice; it does not rule out other futures, but gives a clear heading.

From this direction the approach works backwards into the three artefacts [61]. Horizon 3 [22, 83] addresses the problem the system must ultimately solve, giving the direction concrete form through a service blueprint adapted for human-robot work that positions the concept within the inbound operation [35, 29, 28, 56], making its integration with the surrounding processes and systems explicit. The roadmap translates the adaptive direction into explicit choices and open questions through validation points, so the development can be steered one horizon at a time. The operational requirements specify what the system must satisfy to integrate into the inbound operation across these horizons.

In doing so, the thesis contributes both a concrete operational concept and development path for the autonomous 400 Hz connection at Schiphol, and a transferable approach for translating technically feasible automation into a context-sensitive development path for airport operations.

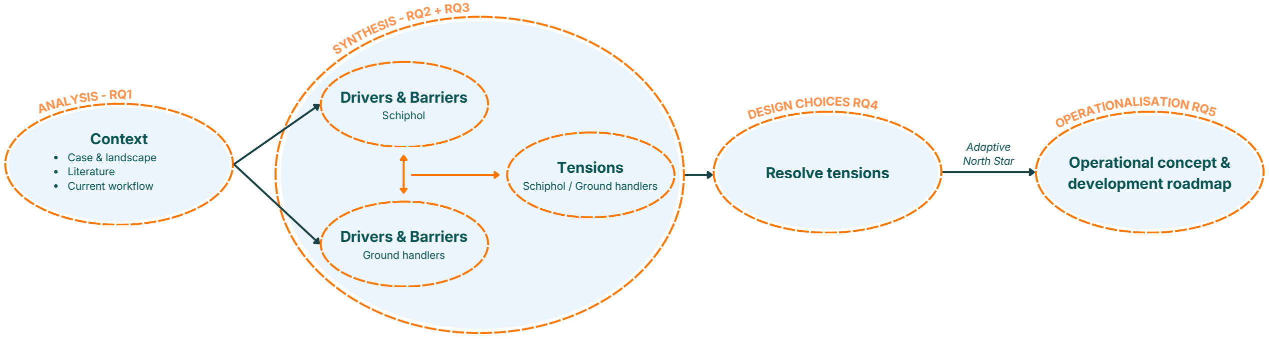

Figure 1.2: Overview of the research approach. Each stage is linked to a research question and chapter.

Chapter 2 | The Context

This chapter sets out the context for the autonomous 400 Hz connection. It first introduces the case behind the project, and then the operational landscape in which an autonomous system must function. The insights in this chapter are based on informal conversations and internal documents.

2. The context

2.1. The Project Case

Royal Schiphol Group and Innovation

Royal Schiphol Group is an airport company that owns and operates Amsterdam Airport Schiphol, Rotterdam The Hague Airport and Lelystad Airport, and holds shares in Eindhoven Airport and Maastricht Aachen Airport [73].

Schiphol's mission is to create a 'thuishaven'[1] for world travellers by serving passengers, airlines and employees, while balancing its operations with the surrounding environment. The strategic vision 2050 is built around four key qualities: Network, Living Environment, Labour, and Service [69].

To work towards these long-term ambitions, Schiphol needs to stay at the forefront of innovation. Part of this innovation is organised within the Innovation Hub, an internal team within Royal Schiphol Group dedicated to developing and piloting innovations across the airport environment. They explore topics ranging from future baggage handling and healthy environments to autonomous airport operations. This research focuses on one specific airside task within that innovation context: the autonomous 400 Hz connection.

The inbound 400 Hz connection

The 400 Hz connection process supplies an aircraft with external ground power once it has parked at the stand: as soon as it is connected, the aircraft can shut down its engines and Auxiliary Power Unit (APU). It is one of the inbound ground handling tasks and is currently carried out manually by ground handlers.

Because the connection is what allows the engines and APU to be switched off, it needs to be done within five minutes of the aircraft arriving at the stand. Delays in this process lead to avoidable emissions. The 400 Hz connection is therefore a time-critical step in the inbound process, and its timing is tied directly to two of the operational challenges that are currently driving innovation at Schiphol Airport: airside emissions and the working conditions of ground handling staff.

Airside emissions and working conditions

At airside there is an elevated concentration of ultrafine particles (UFP). These particles originate from two sources: Diesel Motor Emissions (DME) from ground vehicles, and Vehicle Motor Emissions (VME) from aircraft engines and the Auxiliary Power Unit (APU). Together, these are referred to as Vehicle and Diesel Motor Emissions (VDME). Employees working on the piers and aircraft stands are exposed to relatively high concentrations of UFP, which contributes to unhealthy working conditions [40].

Within current inbound operations, aircraft often cannot taxi directly to their assigned stand because the stand or the required ground handling staff are not yet ready. As a result, the aircraft may have to wait with its engines or APU running, causing preventable emissions. The scale of this problem is reflected in Schiphol's operational data: approximately 10% of arriving flights experience docking issues, which form the operational context in which the autonomous 400 Hz connection becomes relevant.

Increasing passenger volumes further challenge the already existing staff shortage, which can result in more frequent delays and longer aircraft waiting times, leading to additional emissions and higher concentrations of ultrafine particles that negatively affect air quality and the health of airside workers. In turn, unhealthy working conditions can make the work environment less attractive, further reinforcing staff shortages [38]. This reinforcing loop is visualised in Figure 2.1.

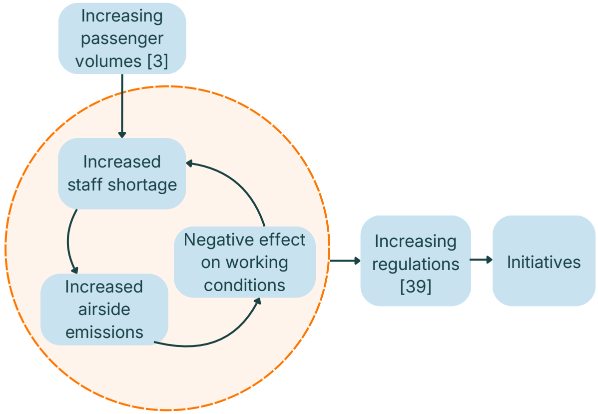

Figure 2.1: Reinforcing loop between increasing passenger volumes, staff shortage, airside emissions, working conditions, and regulations.

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[1] Metaphorically, thuishaven means a place or environment where someone feels safe, comfortable, and truly "at home". It is used to describe a safe haven, a sanctuary, or a place where you can relax and feel secure.

Initiative: Seamless Inbound Flow (SIF)

To reduce these preventable emissions, Schiphol has introduced the VDME programme. This includes the Seamless Inbound Flow (SIF) initiative [40], specifically targeting these 10% docking issues. SIF aims to allow arriving aircrafts to taxi directly from taxiways to the assigned aircraft stand without stopping, improving the efficiency of the inbound process by preventing aircrafts from waiting in front of the stand. This enables aircrafts to shut down their engines, thereby reducing emissions. However, these initiatives are also expected to introduce additional operational complexity due to increased coordination between aircraft movements and air traffic control [71].

Autonomous Airside Operations Vision

It is within this context of SIF and the growing operational complexity that Royal Schiphol Group formally introduced the Autonomous Airside Operations programme in 2020. By 2050, the ambition is that airside vehicles will be replaced by an interconnected fleet of autonomous, emission-free vehicles, and that associated ground processes will be automated [68]. Schiphol has already started to operationalise this long-term vision by developing and testing autonomous initiatives across the airside environment. These initiatives include automated Foreign Object Debris (FOD) detection and removal (Figure 2.2a), self-driving buses (Figure 2.2b) [75] and the development of an autonomous 400 Hz ground power connection system [68]. Similar developments towards airside automation are taking place at airports internationally, see Appendix A.

This project researches the automation of the 400 Hz connection process. Like automated FOD detection, it aims to reduce the dependency on staff during the inbound process up to engine shutdown. In doing so, it directly targets the preventable emissions linked to these docking issues.

(a) Automated Foreign Object Debris (FOD) detection and removal

(b) Self-driving passenger bus [75]

Figure 2.2: Two autonomous airside initiatives currently being piloted at Schiphol

From technical feasibility to operational concept

Schiphol's autonomous airside vision provides a clear long-term direction: airside operations should become increasingly autonomous, emission-free and coordinated. The initiatives described before show that this vision is already being translated into concrete pilots. Yet the vision describes the desired end state without specifying how such systems should function within day-to-day airside operations.

For the autonomous 400 Hz connection, a first Proof of Technology [55] has shown that the physical connection task can be performed by a robotic system. The demonstration established that the robot can navigate to the aircraft stand, detect and open the access panel, and insert the connector autonomously. More details provided in Appendix B.

Between these two points lies a gap: neither the vision nor the Proof of Technology addresses how an autonomous 400 Hz system should be integrated in Schiphol's inbound operation. Demonstrating that a robot can physically perform the task is not the same as knowing how it should function within the operation.

Implications for this project:

The gap is not technical but operational. What is missing is the operational concept: how the autonomous connection should function within the inbound operation, and what development steps are needed to reach that point in practice.

2.2. Operational landscape

Research on automation at Schiphol shows that projects which fail to account for the airside operational context are unlikely to succeed in practice [38]. This section therefore describes the operational landscape in which the autonomous 400 Hz connection must function.

Stakeholders

Automation at Schiphol takes place in a multi-stakeholder ecosystem. A stakeholder analysis was conducted to map the parties involved in and affected by the autonomous 400 Hz connection (Appendix C). To understand the landscape, the stakeholders are plotted on a Power–Interest matrix in Figure 2.3.

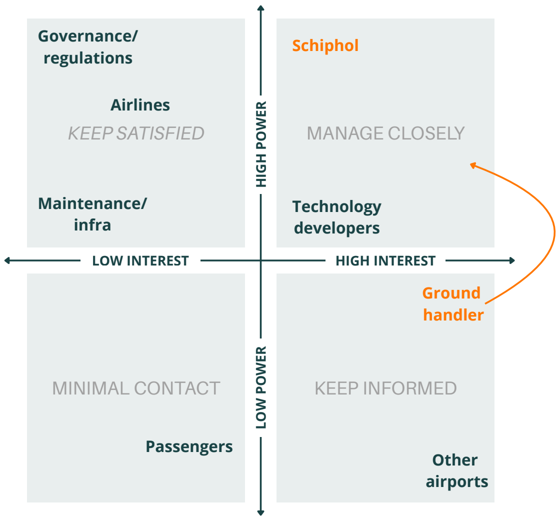


Figure 2.3: Stakeholder Power–Interest matrix. Orange marks the research focus; the arrow places the ground handler at the centre of the analysis - high operational interest despite limited formal power.

This research deliberately focuses on Schiphol Airport and the ground handlers. Schiphol is included as the infrastructure provider: the project originates from Schiphol's autonomous airside vision, and Schiphol provides the strategic, infrastructural and organisational perspective through which the operational insights from ground handlers are interpreted and validated.

The ground handlers are included because the aim is a concept that fits within the inbound operation, and they hold the operational knowledge needed to understand how the system should function in practice. The Power–Interest matrix shows that they combine high operational interest with limited formal decision-making power. They are directly affected by the autonomous 400 Hz connection. For this reason, they are placed at the centre of this research as the primary operational users.

The remaining stakeholders are acknowledged as part of the broader ecosystem surrounding the autonomous connection, but fall outside the active scope of this research.

Operational handling field

Schiphol currently works with six ground handling companies: KLM, Aviapartner, dnata, Menzies Aviation, Swissport, and Skylink, each operating with its own equipment, procedures, and routines. To reduce fragmentation and improve collaboration, Schiphol has started a tender to reduce this number from six to three [82]. This research draws primarily on KLM operations, complemented by Swissport, as representative of the wider handling field.

Airside infrastructure

Figure 2.4 illustrates the pier landscape at Schiphol Airport. At the piers, aircrafts are handled directly at the gate. In addition to the existing piers, Schiphol is currently developing the A-pier. Beyond the pier gates, Schiphol also operates several remote stands, known as buffer positions, which are not directly connected to a gate and are increasingly used for aircraft handling operations.

The layout of piers, platforms and buffer positions differs across the airport. These differences are the result of variations in construction period and the type of aircraft and handling activities accommodated. Consequently, the context of aircraft handling is not uniform across Schiphol.

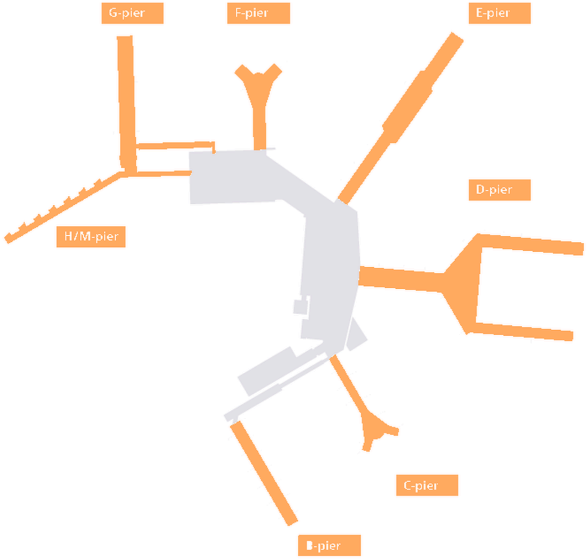


Figure 2.4: Layout of the piers at Amsterdam Airport Schiphol. The pier configurations differ across the airport, illustrating the non-uniform context for autonomous 400 Hz connection [74]

Aircraft type: WiBo research focus

Schiphol handles both Narrow-Body (NaBo) and Wide-Body (WiBo) aircraft. These categories differ in turnaround duration, parking procedure and 400 Hz connection requirements; a full comparison is given in Appendix D. NaBo aircraft generally have shorter turnarounds and are often parked by the pilot once the stand is clear. WiBo aircraft have longer turnarounds, require more extensive ground handling and are guided to their stop position using the Visual Docking Guidance System (VDGS).

For the autonomous 400 Hz connection, this distinction matters because the two categories would lead to different system integration and requirements: handling one cable or two, building on the VDGS system or not, and a different perceived value for ground handlers. Within the scope of this project, a focus is therefore needed. This research focuses on Wide-Body operations for two reasons: the VDGS offers a structured digital environment that an autonomous system can build on for coordination, and the manual task is more demanding here, making ground handlers more likely to see an autonomous system as added value. Even within the Wide-Body category, the location of the connection point varies between aircraft, which the autonomous system must be able to handle. Narrow-Body operations remain relevant as a future application context, but fall outside the active scope of this research.

Aircraft stand and safety zones

The aircraft stand is the area where an aircraft is positioned during boarding, servicing, and ground handling, an area with limited space. At Schiphol, this area is divided into operational zones that regulate the positioning of aircraft, equipment, vehicles and personnel. These zones include the Equipment Restraint Area (ERA), Equipment Staging Area (ESA), Equipment Parking Area (EPA) and No Parking Areas (NPA), areas set by IATA (International Air Transport Association) [44].

These zones regulate where equipment and vehicles may be during handling (Figure 2.5). The ERA in particular must remain clear during docking and pushback, which directly constrains when and where the autonomous system may be active.

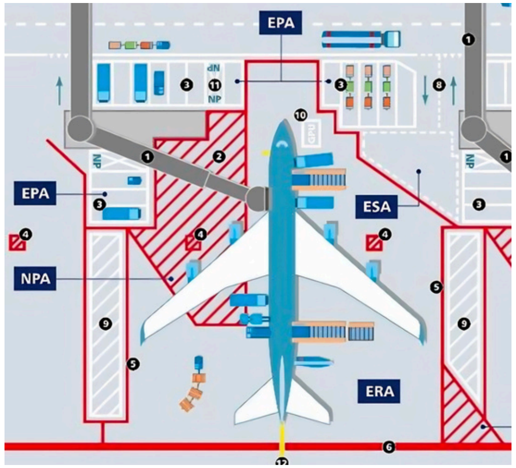


Figure 2.5: Aircraft stand with its IATA operational zones, which define where the autonomous system may be active or positioned

Ground power infrastructure

Since 2010, Schiphol has been phasing out diesel-powered Ground Power Units (GPUs) and replacing them with Fixed Power Units (FPUs), which supply electricity through the gate infrastructure for aircraft systems. For locations where no fixed solution is available, Schiphol developed a mobile electric Ground Power Unit (e-GPU). Schiphol therefore uses two electric methods to supply parked aircraft with ground power: fixed power through FPUs and mobile power through e-GPUs (see Figure 2.6).

The FPU configuration itself also differs across the airport. At most stands it is installed as a standing unit on the so-called FPU island, located outside the ERA close to the connection point, whereas at the newly developed A-pier it is mounted underneath the passenger boarding bridge (PBB). The FPU is the standard infrastructure for ground power at the stand, and Schiphol is moving towards FPUs across the whole airport, making it the main interface an autonomous 400 Hz connection has to work with. That interface is not fixed, however: the under-bridge mounting may become more widespread if it proves successful, as it occupies less space on the VOP. The autonomous system should therefore be able to operate with the FPU in either configuration.

Design conditions from the operational landscape:

Stands and FPU configurations vary across the airport, and connection points differ per aircraft type, so the system cannot be built around one fixed layout but must work across these differences. Within each stand it also has to remain outside the safety zones until the aircraft is parked, then find a safe, workable route to it through the limited margins where other handling runs in parallel.

Figure 2.6: Electric ground power configurations at Schiphol: standing FPU on island (left), an FPU mounted underneath the PBB at the A-pier (centre), and a mobile e-GPU (right)

Chapter 3 | Theoretical Approach

This chapter sets out the theoretical lens and design approaches on which this research builds. It first establishes why the autonomous 400 Hz connection is not a purely technical challenge but also depends on how it fits the people and practices around it, then which principles its integration into the operation must meet, and finally how these are translated into a concrete operational concept through a set of design approaches.

3. Theoretical Approach

3.1. Autonomous connection as a socio-technical design challenge

Two theoretical perspectives frame how the system should be designed for an airport environment. The Multi-Level Perspective positions the innovation within Schiphol's broader transition and explains why operational fit is essential, while socio-technical systems theory, extended for human-robot teams, provides principles on how the connection should be developed.

Positioning the innovation: the Multi-Level Perspective

The Multi-Level Perspective (MLP) provides the wider view, relating an individual innovation to system-level change across three levels: the macro landscape, the meso socio-technical regime, and micro niche innovations (Figure 3.1) [34]. In this case, the landscape pressures described in Chapter 2 destabilise the existing airside regime of manual ground handling, opening a window for niche innovations. Schiphol's Autonomous Airside Operations programme can be understood as such a niche: a strategic response to landscape pressures that aims to fundamentally reconfigure how airside operations are organised. The implication that matters here is that transition only occurs when a niche aligns with the pressures and practices of the existing regime, so without operational fit a technically feasible system is unlikely to succeed [38]. How such alignment should be designed is what socio-technical systems theory addresses.

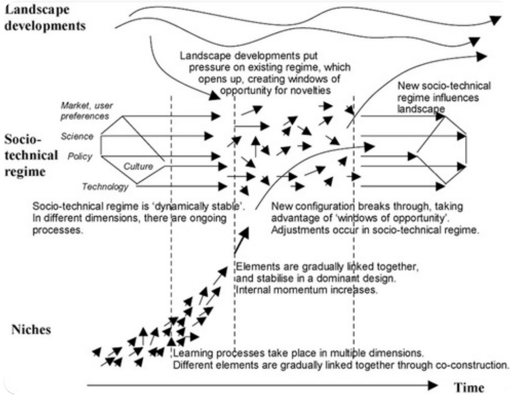
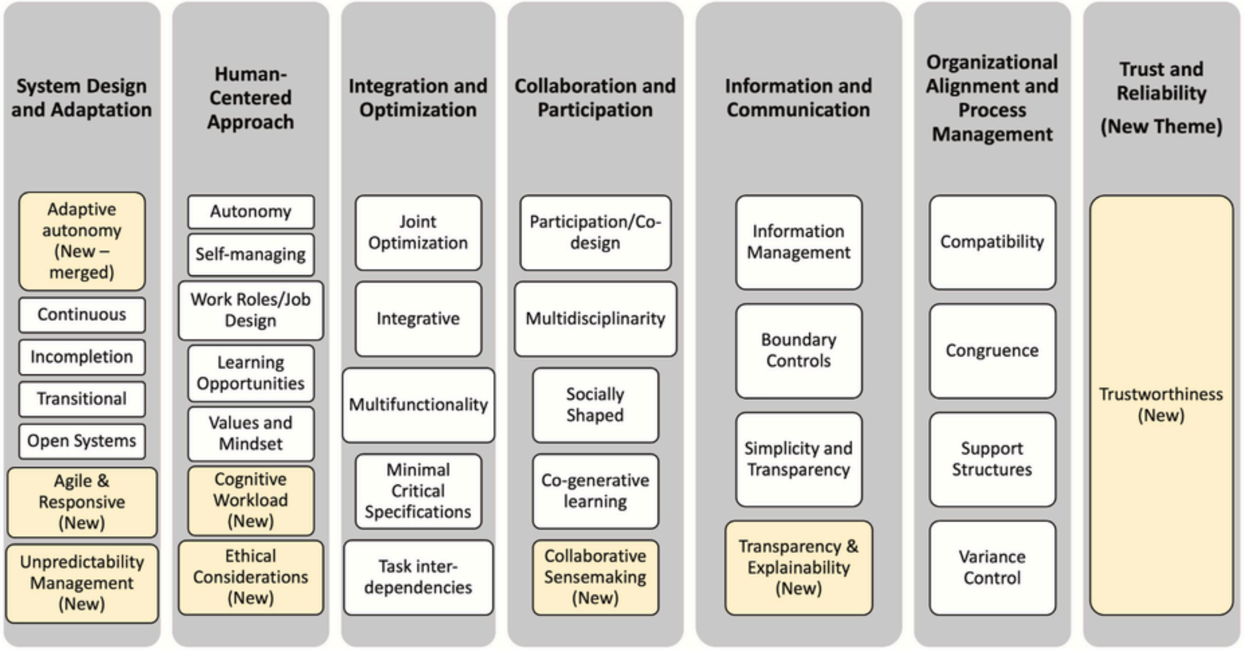


Figure 3.1: The Multi-Level Perspective, showing how landscape pressures destabilise the existing socio-technical regime and create windows of opportunity for niche innovations to emerge [34].



System Design and Adaptation
- Adaptive autonomy (New – merged)
- Continuous
- Incompletion
- Transitional
- Open Systems
- Agile & Responsive (New)
- Unpredictability Management (New)

Human-Centered Approach
- Autonomy
- Self-managing
- Work Roles/Job Design
- Learning Opportunities
- Values and Mindset
- Cognitive Workload (New)
- Ethical Considerations (New)

Integration and Optimization
- Joint Optimization
- Integrative
- Multifunctionality
- Minimal Critical Specifications
- Task inter-dependencies

Collaboration and Participation
- Participation/Co-design
- Multidisciplinarity
- Socially Shaped
- Co-generative learning
- Collaborative Sensemaking (New)

Information and Communication
- Information Management
- Boundary Controls
- Simplicity and Transparency
- Transparency & Explainability (New)

Organizational Alignment and Process Management
- Compatibility
- Congruence
- Support Structures
- Variance Control

Trust and Reliability (New Theme)
- Trustworthiness (New)

Figure 3.2: Human-Robot Team design principles organised across seven themes [6]. Principles highlighted in yellow are new additions to the traditional STS framework

Socio-technical systems theory and the human-robot team framework

The socio-technical systems (STS) theory holds that organisational effectiveness depends on the joint optimisation of the social and technical systems [62]. An autonomous system at Schiphol therefore cannot be treated as a purely technical solution: it must align with organisational goals, user needs, work practices, and existing operational constraints, since a purely techno-centric approach often leads to failure in practice [58, 13].

Classical STS theory was largely developed around stable technologies to which human operators had to adapt [6]. The autonomous 400 Hz connection is different, as learning is bidirectional: ground handlers adapt to the robot while the robot's behaviour is refined as operational experience grows [58, 6]. To account for this, the project uses the STS framework recently extended for Human-Robot Teams (HRTs) [6], shown in Figure 3.2, which adapts established STS principles and adds new ones for robot teaming.

This HRT framework is used as the organising structure of the chapter. Not all principles are equally relevant at every stage [6], so at the design stage this research focuses on those most relevant to fit the connection within the operation. Two groups of principles follow: those concerned with how the system integrates into the operation, discussed in the next section, and those grouped under System Design and Adaptation, which define how the system should be developed over time and are returned to in Section 3.3.

3.2. Principles for integrating automation into the operation

The perspectives before share the implication that a technically capable system creates value only if it fits the operation it enters. Because this research focuses on Schiphol and the ground handlers, the principles that matter most are those that shape how the system fits their daily operation. Three are therefore central at this design stage: compatibility with existing workflows, a clear human-robot role division, and transparency and trust.

Compatibility with existing workflows

Automation often fails when it does not fit the routines and tasks of the workers who interact with it [38, 90]: solutions that appear promising in pilot settings may fail to migrate into real-world operational contexts. In the HRT framework this corresponds to the principles of compatibility and task interdependencies [6]. For the autonomous 400 Hz connection, this means the system should be designed around the existing turnaround process, triggered at the right moment, and able to operate without disrupting surrounding handling activities. This is why the current workflow is mapped in Chapter 4 and why ground handler involvement needs to be maintained throughout development.

Clear role division

Automation is often imagined as reducing dependence on human labour, but autonomous systems rarely simply replace human work [17, 38, 57]. Involvement continues after implementation, with roles such as safety, monitoring, and supporting operators emerging in autonomous airside projects [4]. Roles therefore need to be defined explicitly [38].

Role division is not a binary choice between the human and the robot. Autonomy ranges along a spectrum, from fully manual operation by the ground handler to full robot autonomy, and responsibility for sensing, planning, and acting can be allocated anywhere in between. To structure this division for the concept, the project uses the Levels of Robot Autonomy (LORA) framework [15], which allocates responsibility between human and robot across ten levels of autonomy. An overview of these levels is given in Appendix E.

Where the connection should sit on this spectrum depends on the capabilities of both actors (Figure 3.3): robots excel at repetitive, physically demanding, bounded tasks requiring precision and endurance [6, 33, 64], while humans remain essential for improvisation, contextual understanding, and exception handling [6, 9]. For the 400 Hz connection, the physical execution aligns with robotic strengths, while navigating the dynamic stand environment and handling exceptions stays with the ground handler. As robotic perception and AI develop [49], this allocation may shift towards higher autonomy, reinforcing the adaptive approach in Section 3.3.

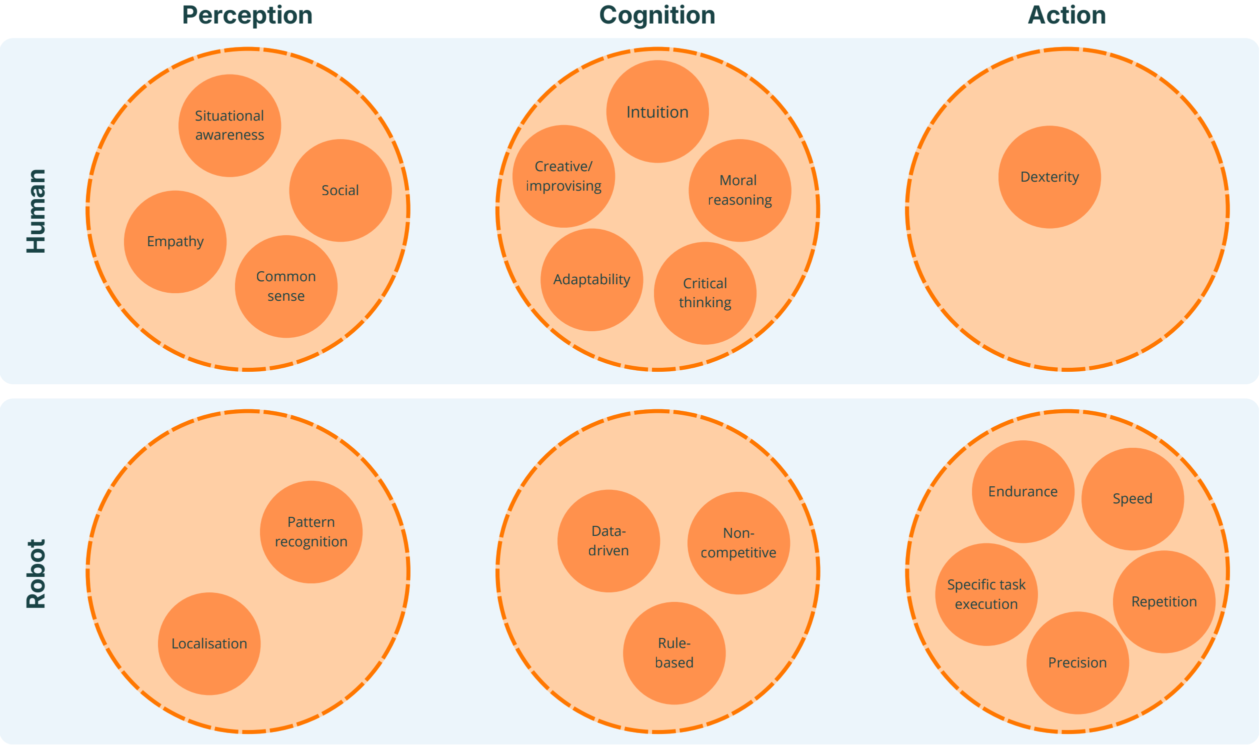


Figure 3.3: Human and robot capabilities across perception, cognition, and action, illustrating where each actor adds most value in a Human-Robot Team.

Transparency and trust

In human-automation systems, transparency means that the system's actions are visible and understandable to the user [79]; in the HRT framework this maps onto the principles of transparency and explainability and of trustworthiness [6]. Transparency is especially important in safety-critical environments, where unexpected system behaviour increases cognitive workload and compromises decision-making [80]. Trust is further shaped by predictability and the ability to intervene: when a robot behaves unpredictably or cannot be stopped, trust decreases [42, 54, 87]. For the autonomous 400 Hz connection, the system must therefore communicate its current state, intended actions, and failures clearly, so the ground handler understands what the system is doing, when attention is required, and when to intervene [20, 6, 48]. Without transparency and trust, even a technically reliable system risks being bypassed in daily practice.

Related work: from a proven technology to operational integration

The previous principles give guidance to move from a technically feasible technology towards an automation concept that can be meaningfully embedded in Schiphol's operation. This section looks into prior works and analyses challenges other studies identify in the integration of autonomy into the organisation. Studies of automation in practice show that it rarely substitutes for human labour as expected; instead it changes the tasks and responsibilities towards less visible forms of monitoring, troubleshooting, and coordination as workers compensate for system limitations and make the technology work in practice [12, 17, 63, 30]. Work on technology integration argues that, for organisations that integrate rather than develop a technology, a central challenge is fitting it into existing structures and work practices, so that success depends less on the technology itself than on organisational readiness and operational fit [38, 24, 78].

What these works have in common is that they recognise the challenges after the technology is shown feasible. Research on the 'last mile' of automation describes this distance between a system that performs in a pilot and one that becomes trusted and used in everyday work [41, 19]. Closing this gap is not a matter of more evidence: design research shows that these design principles discussed above do not by themselves translate into clear choices about a future system [81], and that this translation is particularly demanding for AI-based concepts, where concepts must align technical feasibility with meaningful use for the user [92]. The literature therefore identifies the difficulty and offers general principles for it, but stops short of prescribing how a specific system should be configured in relation to the procedures, roles, and routines of a particular operation.

Recent airport automation research reinforces that such configurations are best treated as iterative rather than fixed, because roles, fallback, and workflow changes tend to surface only in practice [36]. This research addresses that translation step, turning principles into a concrete, workflow-level operational concept. The next section sets out the design approach used to do so.

Implications for the concept:

Taken together, the three principles define what the autonomous 400 Hz connection must meet. They imply that the system should:

- Fit within the turnaround and not disrupt other ground handling processes (workflow compatibility);
- Maintain a clear role division between the ground handler and the system, defining what each confirms, monitors, or takes over (role division);
- Give a clear signal when it is not working properly, enable shared situational awareness, and allow operators to intervene in or stop its operation (transparency and trust).

These implications are the direct input for the design considerations developed in Chapter 4.

3.3. Translating principles into a design approach

The principles above describe what integration must achieve, but not how to reach a concept. This research therefore combines two design approaches: speculative design, to set a direction without fixing the outcome too early, and user-centred and co-design, to keep that direction grounded in the operation.

Designing under uncertainty

The System Design and Adaptation principles of the HRT framework imply that the concept must give direction without fixing the outcome too early [6]. Together they frame the autonomous 400 Hz connection as a system to be developed incrementally and iteratively rather than specified once [36].

This has a direct methodological consequence: not every design choice can be settled now, as some can only be validated through pilots, further development, and the involvement of additional stakeholders. This unknown underpins the roadmap, validation points, and requirements in Chapter 7.

Speculative design

The autonomous 400 Hz connection requires a direction that remains open to change, which is difficult: too much direction fixes the outcome too early, while too little leaves the development without a goal to work towards. Schiphol shows this in practice, as a long-term vision for autonomous airside operations exists, but the concrete steps towards it do not. The design must therefore be actionable today while remaining open to adaptation as operational conditions, technology, and stakeholder needs evolve.

Such future directions are often approached through prediction and forecasting, yet Dunne and Raby [26] argue that attempts to pin down the future are repeatedly unreliable; instead, possible futures are used to understand the present and to discuss which futures are desirable. From this perspective, design is not about predicting the future, but about shaping present-day choices in ways that make more desirable futures more likely [26, 53], moving beyond the probable towards the preferable, what Auger [10] calls the 'perceptual bridge' (Figure 3.4). This is especially useful here because it lets ground handlers and Schiphol operations, as non-designers, engage with an abstract future technology in a creative and meaningful way [84, 7].

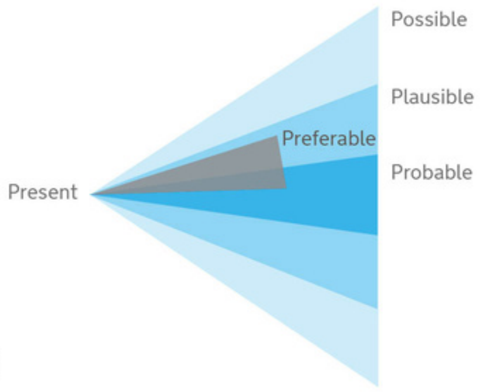


Figure 3.4: Speculative design positions the preferable future beyond the probable, guiding present-day design choices [26].

An adaptive take on the North Star

For this project, speculative design is used to create direction by developing a shared ideal for the future 400 Hz connection process. To give this direction concrete form, the project draws on the concept of a North Star: in product strategy, a single guiding objective that sets a destination while leaving the route open [5]. In that conventional use, the North Star is treated as essentially fixed and revised only when the strategy shifts. For the autonomous 400 Hz connection this is insufficient: the concept cannot be fixed as a finished endpoint, but must evolve as operational experience, technology, and infrastructure develop, in line with the System Design and Adaptation principles. This research therefore makes adaptation a built-in design principle rather than an occasional correction, and creates the term Adaptive North Star: a directional concept that gives a shared destination while explicitly building in moments for iteration. As Figure 3.5 shows, different possible futures share the same starting point, so that the first decisions taken today remain valid across multiple directions.

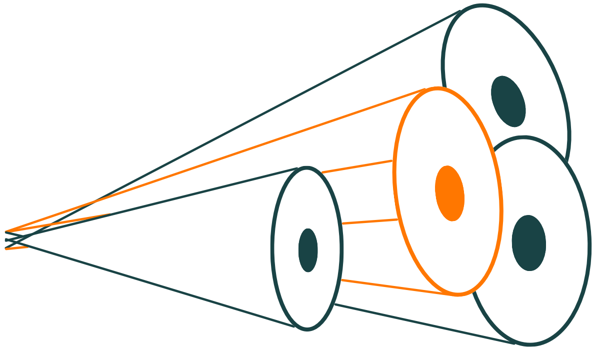


Figure 3.5: The Adaptive North Star: a shared starting point allows direction to be set while leaving room for adaptation over time.

User-centred and co-design

The autonomous 400 Hz connection is embedded in a multi-stakeholder ecosystem in which actors have different responsibilities, interests, and operational knowledge [37]. Its value therefore depends not only on technical capability, but also on whether these stakeholders can and will work with it in practice.

User-centred design requires more than thinking about or for users; it requires engaging with them directly [85]. In this project, this means involving ground handlers and Schiphol operations as stakeholders with direct operational knowledge of the connection, since ignoring their perspectives can lead to misinterpretation and integration challenges [37]. This does not mean users alone define the solution: they are experts in their own work, while the designer translates this input into concepts that also weigh technical possibilities, organisational constraints, and conflicting interests [85]. User-centred and co-design are therefore used to combine operational expertise with design reasoning, so that the concept addresses real problems and is accepted by the people who work alongside it.

Synthesis and research implications:

Together, these perspectives frame the autonomous 400 Hz connection as a socio-technical challenge in which theory, principles, and design approach reinforce one another. This leads to several implications for the project. It must be designed as part of its surrounding work system: given that the technology already works, success now depends on operational integration. Its integration is governed by three principles, which define what any concept must meet but not how to configure it for this operation. Because that configuration cannot be fixed in advance, the concept is developed as an adaptive direction rather than a finished endpoint, for which this research introduces the term Adaptive North Star. And because it can only be judged workable by those who operate it, that direction is set through speculative design and grounded in operational practice through co-design with operators.

Chapter 4 | Current 400 Hz Connection

This chapter examines how the 400 Hz connection currently works in practice. It first maps the workflow and its operational dependencies, then the outcomes the current process produces, and finally the developments already reshaping its context. Together with Chapter 2 and the principles from Section 3.2, these are translated into the design considerations for the autonomous connection system.

4. Current 400 Hz Connection

4.1. Method

A qualitative research design was used to map and analyse the current 400 Hz connection workflow at Amsterdam Schiphol Airport. Formal work procedures provided a structural baseline but did not capture how the task is performed in practice, nor the operational dependencies, timing pressures, and informal workarounds that shape daily execution and ultimately determine integration of the autonomous system. Because no single source captures both the prescribed and the actual process, the research combined document analysis, airside observations, in-depth interviews, and shadow shifts, a combination that supports a contextual understanding of work practices in complex operational settings [89]. The research was structured in two sequential phases.

Phase 1: Workflow mapping

The initial workflow map was constructed using KLM's formal work procedures and subsequently validated through two airside observations. These observations focused on how the task sequence unfolded in practice, the information flows and communication between actors, and how the connection process interacted with surrounding stand activities. The resulting map served as the analytical foundation for Phase 2.

Phase 2: Operational understanding

Fourteen semi-structured interviews were conducted with participants from Schiphol and KLM, covering both the infrastructure-provider and the user perspective. The interviews served to build a broad operational understanding of the connection process and its surrounding context. The topics were adapted iteratively as understanding developed across sessions. The interview topics with the full list of participants and their roles is included in Appendix F.

Two shadow shifts were conducted to observe the 400 Hz connection process within its everyday operational context. Where interviews capture how actors describe their work, shadowing additionally surfaces contextual behaviour, implicit routines, workarounds, and pain points that formal procedures and interviews may not capture [25, 23]. Participatory elements were included alongside observation, allowing parts of the handling task to be experienced directly. One shift was conducted in a Narrow-Body context and one in a Wide-Body context, both alongside shift leaders.

4.2. The current workflow

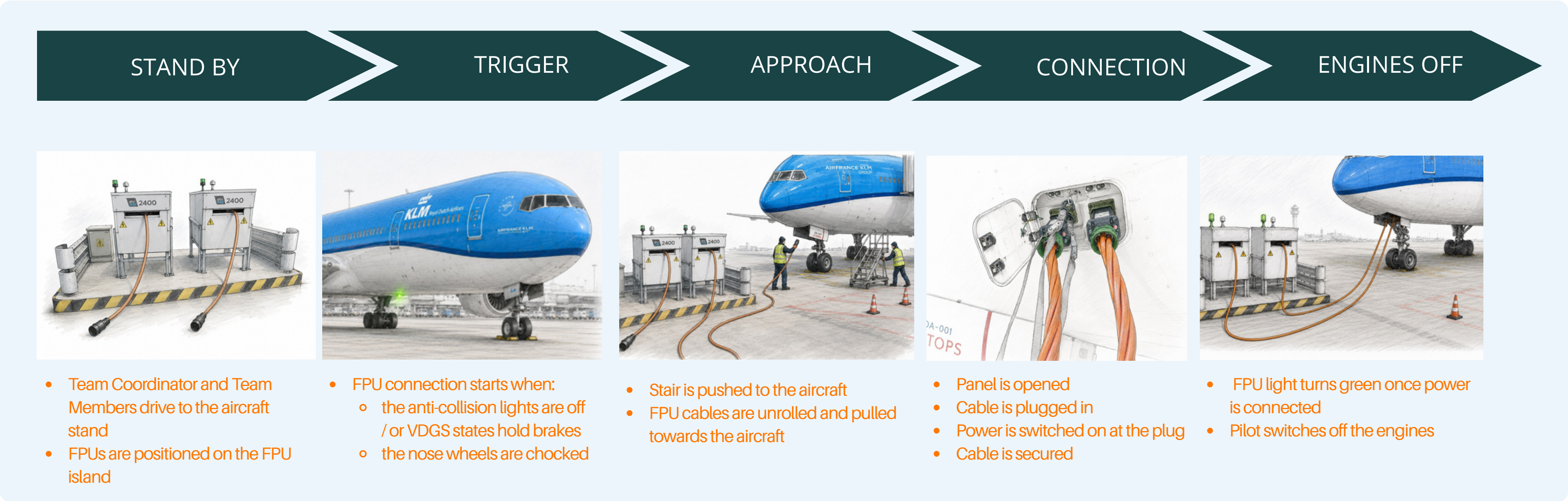
Section 3.2 established workflow compatibility as a key principle: an autonomous system only fits if it accounts for the existing process around it. This chapter makes that process visible. As established in Section 2.2, this research focuses on the Wide-Body context; the current workflow is therefore mapped for Wide-Body operations.

Five-phase workflow structure

Based on the workflow map from Phase 1 and validated through the interviews and shadow shifts, the connection process was structured into five consecutive phases, each with a distinct goal. This structure also serves as the basis for mapping the future autonomous workflow in Chapter 7.

1. **Standby:** the phase before aircraft arrival, in which the ground handler and equipment need to be ready on time.
2. **Trigger:** the moment or signal that indicates when the connection process may start.
3. **Aircraft approach:** the movement of the ground handler and equipment towards the aircraft.
4. **Connection:** the physical connection of the 400 Hz cable to the aircraft.
5. **Engines off:** the moment external power is available and the aircraft can switch off its engines and/or APU.

Figure 4.1 illustrates these five phases and the key operational actions within each.



STAND BY

- Team Coordinator and Team Members drive to the aircraft stand
- FPUs are positioned on the FPU island

TRIGGER

- FPU connection starts when:
    - the anti-collision lights are off / or VDGS states hold brakes
    - the nose wheels are chocked

APPROACH

- Stair is pushed to the aircraft
- FPU cables are unrolled and pulled towards the aircraft

CONNECTION

- Panel is opened
- Cable is plugged in
- Power is switched on at the plug
- Cable is secured

ENGINES OFF

- FPU light turns green once power is connected
- Pilot switches off the engines

Figure 4.1: The current 400 Hz connection workflow structured into five consecutive phases, showing the key operational actions within each phase. Image generated with the assistance of ChatGPT.

4.3. Operational dependencies in the current workflow

The five-phase structure above provides a task-level overview, but does not capture the operational dependencies that shape when and whether each task can proceed. To make these dependencies visible, the workflow is translated into a service blueprint.

Method: service blueprinting

The blueprint distinguishes between frontstage actions: the tasks directly associated with the physical connection at the stand, and backstage actions: the supporting processes and system signals that govern their timing and sequencing [35, 29]. Rather than a customer's user journey, it here follows the operational journey of the connection itself. A further reason for this method is that the same blueprint can later be adapted into a multi-actor map centred on the robot, which is shown as well suited to clarifying the distribution of tasks, roles, and authority between humans and robots [28, 56].

The connection as an interdependent task

The current blueprint (Figure 4.2) was developed iteratively and validated during interviews. It reveals that the 400 Hz connection is not an isolated physical task. Before the ground handler can approach the aircraft, the stand must be cleared, the aircraft must be docked, and specific safety conditions must be confirmed; at the other end of the sequence, the ground-power-available signal enables engine shutdown by the flight crew. Two operational outcomes emerge from this workflow, marked with a star in the blueprint and discussed in Section 4.4.

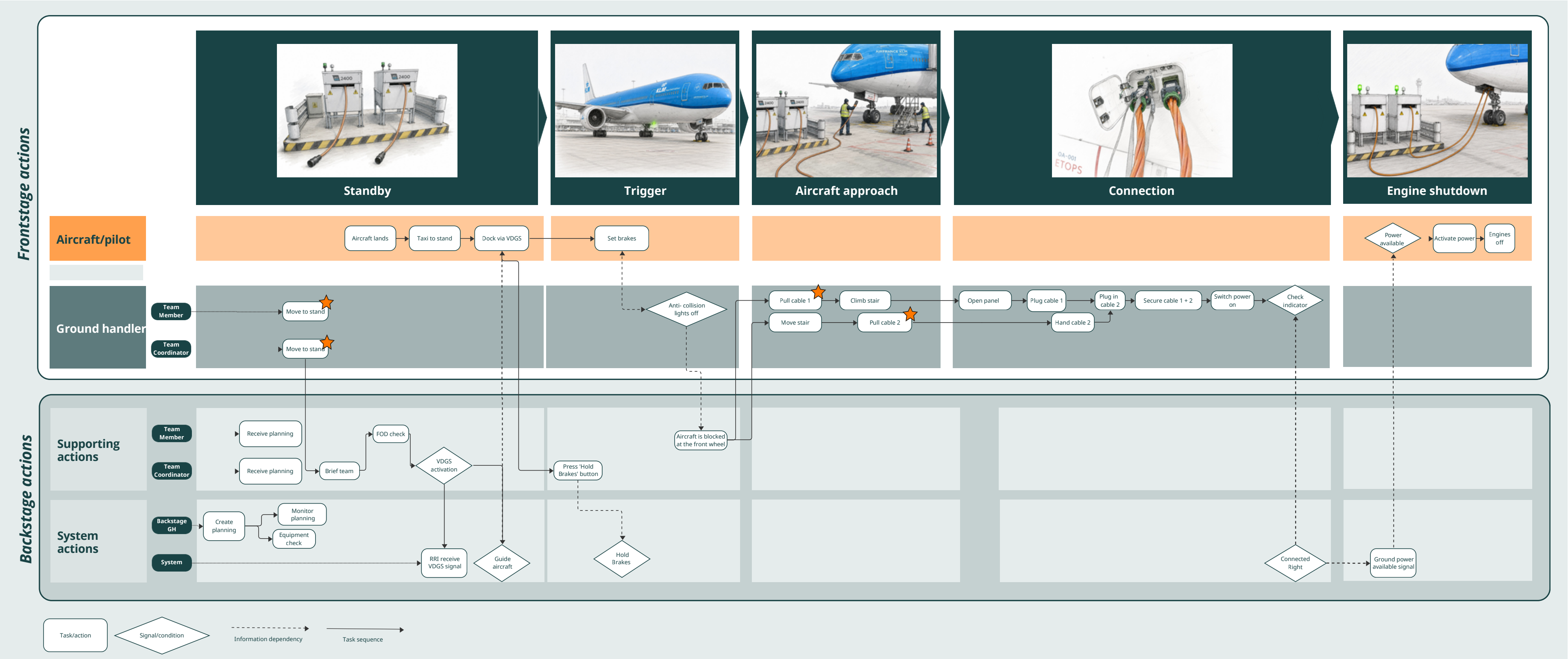


Figure 4.2: Service blueprint of the current 400 Hz connection workflow, following the operational journey of the connection and showing frontstage actions, backstage actions, and the operational dependencies. Image generated with the assistance of ChatGPT.

Implications for autonomous connection:

Because the connection may only proceed once the surrounding conditions are met, the system cannot act on a fixed schedule but has to be triggered by, and respond to, the state of the stand. Integrating into this sequence of dependencies, rather than performing the connection in isolation, is therefore the central design task. How it does so is shown later in a new service blueprint that maps the autonomous workflow with these dependencies included (Chapter 7).

4.4. Current workflow outcomes

The autonomous 400 Hz connection was motivated by two concerns: that the connection is not always made on time, and that the task itself is physically demanding. Mapping the workflow and analysing the observations, interviews, and shadow shifts confirmed both and exposed their underlying causes.

Timely connection

As described in Section 2.1, a delayed 400 Hz connection keeps the aircraft on its engines or APU longer than necessary, causing preventable emissions. This research identified three underlying causes of this delay, each consistently reported across both stakeholders. Their relative weight is not yet quantified.

Planning dynamics and last-minute changes
The inbound operation is subject to continuous replanning: shifting arrival times and gate reassignments affect staff positioning and availability, compressing the time available for pre-arrival preparation.

Misplaced ground support equipment
Schiphol currently operates with six licensed ground handling parties, each responsible for its own Ground Support Equipment (GSE). Due to insurance constraints, parties may not reposition another handler's equipment. When GSE is incorrectly positioned at the stand, it can obstruct aircraft entry and cause delays.

Work culture and mentality
Ground handlers in some cases wait for visual confirmation of the aircraft before beginning preparatory activities, even though procedures prescribe starting earlier. As a result, the connection process starts later than intended.

Physical workload

The physical demands of the task form the second outcome. Connecting two heavy FPU cables, sometimes requiring stair access, places a recurring load on handlers in Wide-Body operations. The interviews and shadow shifts consistently identified the connection task as one of the most negatively experienced elements of the docking process.

Implication for autonomous connection:

Of the three delay causes, an autonomous system mainly acts on planning dynamics, by being available on time where no operator can be present; misplaced GSE and work culture fall outside its scope. Planning dynamics, together with taking over the physically demanding connection, defines the two outcomes autonomous connection targets directly.

4.5. Supporting developments in the current operation

Several ongoing developments shape the conditions for an autonomous 400 Hz connection: they show which parts of the current workflow are already being improved or monitored, and they identify systems a future autonomous system may need to integrate with or build upon.

Digital coordination for autonomous operations

Schiphol is building the digital environment that autonomous airside operations depend on. Turnaround Insights, also referred to as DeepTurn, uses stand camera images and AI to translate handling activities into operational data (Figure 4.3), helping identify where delays emerge [65].

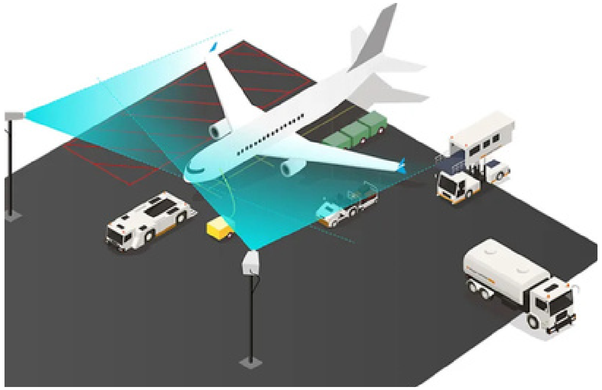


Figure 4.3: DeepTurn cameras installed at aircraft stands, using AI to translate handling activities into operational data for turnaround monitoring [65].

This data feeds the coordination layer being developed for autonomous operations. The Ramp Orchestration System (ROS) uses flight, radar, and turnaround data to determine when and where autonomous ground tasks should take place, sequencing and triggering services such as FOD sweep, VDGS activation, and the 400 Hz connection, while the robots retain local control over execution [70].

It is complemented by OTISS, which orchestrates mixed autonomous and human-driven airside traffic [77], and Wilbur, a real-time dashboard for data-driven capacity decisions [67].

Stand readiness and marshal support

Within the SIF programme, Schiphol is piloting dedicated marshal teams to support timely stand readiness. A Ramp Readiness Indicator (RRI), on the Wilbur platform, monitors whether a stand is cleared for inbound docking, using VDGS activation as its primary signal; it turns orange ten minutes before the expected inbound time if the VDGS is not yet active, and red at five minutes. DeepTurn cameras complement it by showing whether a handling team is already present.

This matters because the marshal logic, dispatching support when no handler is present on time, mirrors the availability problem an autonomous connection aims to solve, making the pilot a relevant source of operational experience.

Clean VOP

Schiphol is also addressing the two delay causes that fall outside the autonomous system's scope: misplaced GSE and work culture. Using the same DeepTurn cameras, it is developing a clean VOP trigger that detects whether GSE is incorrectly positioned before the aircraft arrives, so that authority officers can intervene early and hold the responsible handling party accountable. For the autonomous system this matters directly, as it can only initiate the connection once the VOP is clear.

Implication for autonomous connection:

These developments show that the autonomous connection would not be introduced in isolation: the surrounding operation is changing alongside it. For the concept, this means these parallel developments have to be taken into account when integrating the system into the organisation, designing for an evolving environment.

4.6. Design considerations

The insights from this chapter, combined with the contextual insights from Chapter 2 and the principles from Section 3.2, are translated into concrete design considerations for the autonomous 400 Hz connection: what the system must satisfy to integrate into the operation. Each consideration is linked to its underlying insight in Table 4.1 at the next page.

Table 4.1: Design considerations for the autonomous 400 Hz connection, each derived from contextual and theoretical insights from Chapters 2, 3, and 4

Considerations	Insights	Section
Be present on time where no operators are available	*Approximately 10% of arriving flights experience docking issues; the main reason an autonomous connection is needed is that ground handling staff is not present at the stand on time when the aircraft arrives.*	*Section 4.4*
Reduce physical demands	*Connecting two heavy FPU cables, sometimes requiring stair access, places a recurring load on handlers in Wide-Body operations.*	*Section 4.4*
Have a clear role division between the ground handler and the system	*Human involvement continues after automation; roles such as safety, monitoring, and supporting operators emerge in autonomous airside projects but are often left undefined.*	*Section 3.2*
Remain outside the safety zones until the aircraft is parked	*The ERA must remain clear during docking and pushback; any equipment or vehicle in this zone causes safety violations.*	*Section 2.2*
Not disrupt other ground handling processes	*Automation fails when it does not fit existing routines. The connection runs alongside other ground handling processes on the stand, so disruption risks both turnaround delays and integration failure.*	*Section 3.2 / 4.3*
Follow a safe and workable route to the aircraft	*The stand layout is governed by IATA safety zones that restrict where equipment may move, while multiple actors and pieces of equipment are active simultaneously within limited space.*	*Section 2.2 / 4.3*
Give a clear signal when not working properly	*In safety-critical environments, operators cannot act on problems they cannot see; unclear system behaviour increases workload and risk.*	*Section 3.2*
Enable shared situational awareness	*Without shared awareness of the task state, the handler cannot know when to act and when to step back, making situational clarity a prerequisite for safe human-robot collaboration at the stand.*	*Section 3.2*
Handle the busyness and dynamics at the stand	*The stand environment is dynamic: vehicles, equipment, and personnel move continuously within limited space and time margins.*	*Section 4.3*
Allow operators to intervene in or stop its operation	*Trust in autonomous systems depends on predictability and human oversight; systems that cannot be stopped are not accepted in safety-critical contexts.*	*Section 3.2*
Work with different aircraft types and stands	*Connection point locations differ per aircraft type, and stand and pier layouts vary across Schiphol, creating varying operational conditions.*	*Section 2.2*

Chapter 5 | Operational Positioning:

Drivers, Barriers, and Tensions

This chapter first narrows the design considerations to a single analytical focus: workflow positioning. Then it analyses this positioning in terms of drivers, barriers, and tensions that shape how the connection should be integrated. These tensions form the basis for the design choices developed in Chapter 6.

5. Operational Positioning

5.1. From considerations to workflow positioning

The design considerations cannot all be addressed within one project, so a choice is needed about where the analysis begins.

Method and Result

Two ground handlers, selected for their knowledge of the current connection process, evaluated the operational relevance of each consideration, while three Schiphol innovation practitioners, selected for their involvement in autonomous airside development, assessed the same considerations using an Impact-Effort Matrix (IEM): a tool that prioritises options by comparing expected impact with implementation effort [86]. The simplified result is shown in Figure 5.1; the full matrix is in Appendix G.

The considerations rated both important and feasible share a common thread: they all concern how the system is positioned within the operational sequence, when it should be active, where it should be, and how it fits around other stand processes. This research therefore takes workflow positioning as its analytical focus. This is an explicit scoping choice that shapes the rest of the thesis: operational integration, rather than technical design, becomes the direction in which the concept is developed. Open questions concerning physical and technical realisation, such as how the robot navigates the stand, handles different connection points, or deals with the busyness around it, are not analysed here; they remain valid directions but require technical integration work outside an operational design project, and are carried forward as requirements in Chapter 7.

Implication for research:

What this focus means in practice is that the autonomous connection is analysed from the current workflow as a starting point: not as a new system designed in isolation, but how it fits into the operational sequence that is already there.

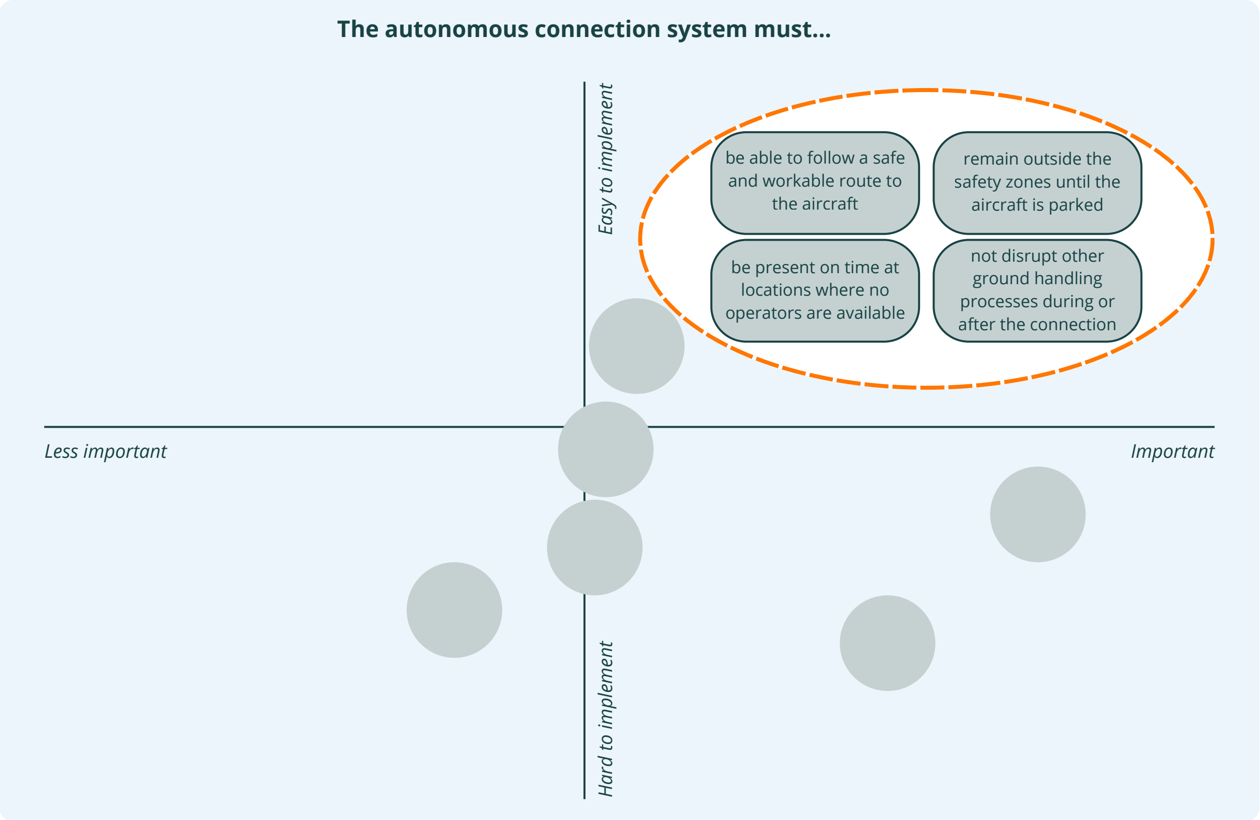


Figure 5.1: Simplified Impact-Effort Matrix of the design considerations. The four considerations in the upper-right quadrant, rated both important and relatively easy to implement, all concern the positioning of the system within the operational workflow. The remaining considerations are shown in grey; the complete matrix is provided in Appendix G.

5.2. Drivers, barriers, and tensions

Integrating an autonomous connection within this workflow raises two questions: what value the autonomous system adds in this operation, and what makes it difficult to integrate. Building on the interviews and the analysis of the existing workflow, the drivers establish the value the system must deliver, and the barriers the conditions it must work within.

The drivers and barriers are not independent: where a driver and a barrier pull in opposite directions, a tension arises, a point where an explicit design decision is needed. The analysis is therefore structured into these three categories, following innovation literature, which distinguishes factors that enable integration from those that complicate it [91, 89]. In line with the stakeholder scope of this research, tensions are limited to where the interests of Schiphol and ground handlers diverge.

Table 5.1: Drivers that motivate the development of an autonomous 400 Hz connection

Drivers	Explanation	Affects
D1: Operational readiness	*The inbound operation is highly dynamic, making it structurally difficult to guarantee ground handler presence at the VOP at the right moment. An autonomous system operates independently of planning variability. (Section 4.4)*	*Schiphol / GH*
D2: Emission reduction	*When the 400 Hz connection is delayed, the aircraft remains dependent on its engines or APU for onboard power, generating preventable emissions at the stand. (Section 2.1)*	*Schiphol*
D3: Physical demands	*The connection task is physically demanding, particularly for wide-body aircraft where heavier cables and additional access equipment are required. (Section 4.4)*	*GH*
D4: Autonomous airside vision	*The autonomous 400 Hz connection aligns with Schiphol's long-term vision for autonomous airside operations and serves as a concrete step towards automated inbound processes. (Section 2.1)*	*Schiphol*
D5: Working environment	*Ground handlers are routinely exposed to engine and APU exhaust during inbound operations. Reducing preventable emissions and keeping personnel away from the VOP contributes to lower UFP exposure and a healthier working environment. (Section 2.1)*	*Schiphol / GH*

Drivers: why autonomous connection is relevant

The drivers explain why an autonomous 400 Hz connection is operationally relevant: they are the motivations the concept needs to address. Table 5.1 gives an overview of each driver, its source, and the perspective it mainly affects.

The following paragraphs elaborate on each driver, drawing directly on the perspectives of ground handlers and Schiphol representatives gathered through the interviews and shadow shifts.

D1: Operational readiness
Fluctuations in flight schedules cause planning to shift continuously throughout the day, making it structurally difficult to guarantee ground handler presence at the aircraft stand at the right moment. As P5 noted, planning efficiently is *"almost impossible, the margins are simply very small"*. From an airport perspective, the requirement is clear: *"an aircraft must always be able to dock at the stand, regardless of whether it arrives early or late"* (P1). An autonomous system addresses this by operating independently of planning variability, contributing, in the terms used by P4, not to speed, but to *"stability"*.

D2: Emission reduction
A delayed connection prolongs engine and APU runtime at the stand. Airlines increasingly avoid APU use, as it is ``*expensive, in 70% of cases not working, and often worse in terms of noise and emissions*'' (P1). Timely autonomous connection directly reduces preventable emissions and their associated impact on local air quality.

D3: Physical demands
Wide-body cable handling is physically demanding. P14 described the current equipment as ``*the worst thing ever added to airside, those things are genuinely a mistake*''. Full task replacement is not required to realise value: P9 argued that ``*just pre-positioning the cable to within half a metre of the aircraft is already a win; that alone is 90% of the gain and easier to implement*''.

D4: Autonomous airside vision
The autonomous 400 Hz connection represents a concrete step towards Schiphol's longer-term ambition of future-proof airside operations. P8 articulated this orientation: ``*do not just look at current staff shortages, but think about how you can be future-proof as an airport*''. This driver positions the project within the broader transition (Section 3.1)

D5: Working environment
Ground handlers are routinely exposed to engine and APU exhaust during inbound operations, observed directly during the shadow shifts. P6 framed the broader principle as follows: ``*Schiphol is not a very healthy environment to work in, so as few people as possible on and around the aircraft stand*''. Distinct from the physical demands of the task itself (D3), this driver concerns exposure to emissions and UFP: a concern for both ground handlers and Schiphol as employer.

Barriers: what makes implementation difficult

The barriers describe the conditions that must be addressed for the autonomous system to function in practice. They establish what the design must overcome and directly inform the requirements in Chapter 7. Table 5.2 provides an overview of each barrier, its source, and the perspective it primarily affects.

The following paragraphs elaborate on each barrier, drawing directly on the perspectives of ground handlers and Schiphol representatives gathered through the interviews and shadow shifts.

B1: Limited space at the stand
Space at the airside is scarce and cannot be assumed. P1 stated that ``*there is very little space at the stands. Space cannot be taken for granted, it is not there*''. This was confirmed during the shadow shifts, where the stand was already densely occupied during inbound handling. P9 framed the resulting design constraint directly: ``*the priority is to take up as little space as possible*''.

B2: Stand and aircraft variation
Stand layouts, FPU positions, and connection point locations vary across aircraft types and stands. As observed during the shadow shifts, the connection point is located differently per aircraft type. P2 confirmed this: ``*there is a lot of variation in aircraft types: they stop at different positions and the connection point sits in a different place*''.

B3: Surrounding processes
The 400 Hz connection takes place alongside other processes. P2 noted that ``*the cable must not obstruct the catering door at the first exit*'', and stated more broadly that ``*if the system interferes with other processes or with the work of ground handlers, implementation will be difficult*''.

B4: Equipment Restraint Area
Stand layout at Schiphol is governed by IATA regulations, including the Equipment Restraint Area (ERA). P11 explained that ``*blueprints define the VOP layout, the ERA is the area around the aircraft that must remain free of equipment during docking and pushback*''. This constrains when and where an autonomous system may be active or positioned, and must be accounted for in both the physical design and the operational workflow.

B5: Certification and approval
Any system that physically interfaces with an aircraft requires certification and approval from aircraft manufacturers and airlines. P4 noted that ``*connecting to the aircraft will take a long time as certification is needed from Boeing and Airbus*''. The PBB automation pilot, which took from 2017 to 2026 to reach operational readiness, illustrates the timescales involved (P6).

B6: Adoption
Trust depends on consistent behaviour over time, as P2 emphasised: ``*half-finished work is dangerous, you need to be able to rely on it; trust comes when it does what it is supposed to do 99% of the time*''. The adoption challenge is not only behavioural but also organisational. P3 drew a direct lesson from prior implementations: ``*Schiphol implements, but the ground handler must ensure it gets used, you*

have to develop it together''. This barrier was further reinforced by the scenario evaluation, in which poor adoption management was identified as the central risk across all three scenarios (Appendix H).

B7: Dependency on preceding processes

The 400 Hz connection can only begin after correct aircraft parking, blocking, and FOD clearance have been confirmed, as revealed by the blueprint analysis in Section 4.2 The autonomous system must therefore be capable of monitoring or receiving confirmation of these upstream conditions before initiating the connection.

B8: Investment and business case

P10 and P3 both emphasised that securing investment requires demonstrating technical readiness, scalability, and a positive business case. As P10 noted, this may only become viable at sufficient scale, as maintenance, lifespan, and service requirements add to the total cost. Beyond financial viability, P10 identified a third condition: *``you need a sponsor, someone from the board who says: we really need to do this''*.

Table 5.2: Barriers to autonomous connection, describing the conditions that must be addressed for implementation

Barriers	Explanation	Affects
B1: Limited space at the stand	*The aircraft stand is a crowded operational environment with limited space, making it difficult to position an autonomous system. (Identified through shadow shifts and interviews, Section 2.2)*	*Schiphol*
B2: Stand and aircraft variation	*Stand layouts, FPU positions, and connection point locations vary across aircraft types and VOPs. (Section 2.2)*	*Schiphol*
B3: Surrounding processes	*The 400 Hz connection takes place alongside catering, baggage handling, and PBB operation. The system must not obstruct these processes. (Section 4.2)*	*GH*
B4: Equipment Restraint Area	*The ERA must remain clear during docking and pushback, constraining when and where the autonomous system may be active or positioned. (Section 2.2)*	*Schiphol*
B5: Certification and approval	*Any system that physically interfaces with an aircraft requires certification and approval from aircraft manufacturers and airlines. (Identified through interviews)*	*Schiphol*
B6: Adoption	*Ground handlers must understand, trust, and accept the system. Without active adoption management, the system risks being bypassed or rejected. (Identified through interviews and scenario evaluation, Appendix H)*	*GH*
B7: Dependency on preceding processes	*The connection can only begin after correct aircraft parking, blocking, and FOD clearance have been confirmed. (Section 4.2)*	*Schiphol / GH*
B8: Investment and business case	*The development and deployment of an autonomous connection system requires significant investment. Justifying this investment depends on sufficient operational volume and a clear business case. (Identified through interviews, Appendix H)*	*Schiphol*

From drivers and barriers to tensions

The drivers and barriers are still two separate lists: one explains why the autonomous connection is operationally relevant, the other what stands in its way. Design happens where the two meet. Where a driver and a barrier pull in opposite directions, and where Schiphol and the ground handlers would resolve that pull differently, a tension emerges [31]: a point where an explicit design decision must be made.

Not every driver and barrier reaches this point. Some barriers are fixed conditions the design simply has to meet rather than points the two parties disagree on; these return as requirements in Chapter 7.

What remains are the genuine conflicts: five tensions, presented in Table 5.3. Each marks a point where the needs of Schiphol and the ground handlers cannot be met at the same time without an explicit design choice, which makes them the starting point for the co-design process in Chapter 6.

Table 5.3: Tensions within autonomous connection, identifying where the requirements of Schiphol and ground handlers diverge and where design decisions must be made

Schiphol	Tension	GH
Scalable and flexible deployment with a viable business case	**T1: Integration**	*Reliable system that is always available at the stand without added coordination*
System operates independently of staff availability	**T2: Human control**	*Ability to monitor, pause, and intervene*
Schiphol-owned and centrally managed equipment	**T3: Ownership**	*Clear responsibility for daily readiness and failure recovery*
System must meet safety certification requirements	**T4: Performance margins**	*System must not be slower than a human handler*
Autonomy over all preceding conditions	**T5: Operational dependencies**	*Clarity on which tasks stay theirs, and when they must be present*

Implication for research:

The autonomous 400 Hz connection cannot be developed as a simple addition to the current workflow: its operational value depends on choices within the concept itself. Each choice concerns how to balance the interests of both groups, a choice between Schiphol and the ground handlers rather than a question the designer can answer. This is why the concept is shaped through co-design: the next chapter brings both parties together to translate the tensions into an explicit, shared direction acceptable to both.

Chapter 6 | From Tensions to Choices:

Co-designing the Adaptive North Star

This chapter turns the five tensions into design choices. It first describes the co-design method and workshop, then presents the desired outcomes that emerged. Based on these outcomes, a design choice is made for each tension. Together, these choices form one guiding direction: the Adaptive North Star.

6. From Tensions to Choices

The five tensions from Chapter 5 each mark a point where the interests of Schiphol and the ground handlers pull in different directions, and an explicit choice is needed: a choice between those interests rather than one the designer can settle alone. This chapter therefore turns the tensions into design choices through co-design.

6.1. Method: Speculative Co-design

A co-creation workshop was conducted with six participants from Schiphol, KLM, and Swissport, list of participants in Table 6.1. The full workshop protocol is provided in Appendix I. The workshop participants are referred to as WPx (Workshop Participant) to distinguish them from the interview participants (Px); several individuals took part in both. They were purposively selected to represent both sides of the tensions: those who work alongside the system in daily operation, and those responsible for developing and implementing it. Bringing both perspectives into the room surfaced how each side weighs the design choices, rather than having the designer resolve them in isolation.

Participants were recruited through existing contacts from the interview phase and through recommendations from within Schiphol and KLM, ensuring that each had direct experience with the inbound connection process or future developments. The group was deliberately kept small: Arcia et al. [8] suggest that groups of four to eight participants work well for most participatory design tasks. The six participants allowed each person to contribute actively while still bringing together multiple operational and innovation perspectives.

The workshop lasted 90 minutes and followed a sequential flow from problem reflection to future visioning, so that a shared understanding of the current situation was established before participants moved towards designing a future process. A pilot session was conducted beforehand to test whether the setup was understandable and to observe how participants engaged with the materials, allowing the protocol to be adjusted before the actual session.

Workshop structure

The workshop consisted of seven phases, each with a specific aim. Figure 6.1 gives an overview of the workshop steps and Figure 6.2 an impression of the setting.

Table 6.1: Participants of the Co-design workshop

Participant	Organisation	Role
WP1	*Schiphol*	*Innovation*
WP2	*KLM*	*Ground handler*
WP3	*KLM*	*Ground handler*
WP4	*KLM*	*Innovation*
WP5	*Swissport*	*Innovation/ operations*
WP6	*Swissport*	*Ground handler*

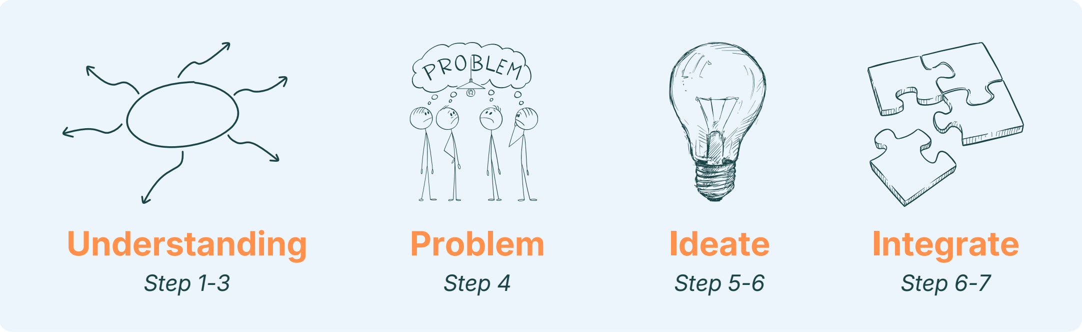


Figure 6.1: Overview of the aim of each workshop step

Step 1: Introduction

The session opened with a brief introduction round in which all participants introduced themselves by name, role, and short icebreaker.

Aim: lower the threshold for participation by letting all participants speak once before the workshop begins.

Step 2: Context alignment

A short presentation introduced the problem context and the current workflow outcomes from Chapter 4. The printed current workflow from Section 4.2 was placed on the table as a shared reference. This ensured that participants from different backgrounds had the same contextual foundation, and that the level of detail introduced in the presentation set the frame for the depth of discussion in the design phases that followed.

Aim: ensure shared understanding of the current workflow and its outcomes, and set the level of detail for the design phases that follow.

Step 3: Case introduction

A speculative case study was introduced: participants were told that the F-pier would be completely rebuilt, and that they had been selected to shape the future connection process for this new pier. This framing was chosen to invite participants to reason freely about what a future connection process could look like, unconstrained by the current physical environment [26, 7].

Aim: remove infrastructural constraints to stimulate out-of-the-box thinking.

Step 4: Problem reflection (Q1)

Using the printed current workflow from Section 4.2 as a reference, participants were asked two questions using colour-coded post-its: what needs to change (yellow), and what would be beneficial to change (pink). The distinction was introduced to separate operational necessities from desirable improvements.

Aim: surface what participants see as necessary versus desirable changes, creating nuance in problem identification.

Step 5: Initial ideation (Q2)

Participants were asked how the identified problems could be addressed. This question served as a bridge between problem reflection and the main design activity.

Aim: bridge from problem identification to future visioning by activating early ideas.

Step 6: Desired future workflow (Q3)

The central activity asked participants to sketch their desired future along three dimensions: the source of power, its routing to the aircraft, and the required infrastructure. Printed A3 sheets of the aircraft and stand supported spatial reasoning, and a process template let participants map the steps of their concept. Clarifying questions deepened the discussion, asking what changes their vision would require, and what it would mean for KLM and Schiphol.

Aim: generate concrete directional visions for the future 400 Hz connection process.

Step 7: Role division (Q4)

To conclude the workshop, participants reflected on how responsibilities could be distributed in the future process and the conditions under which trust in an autonomous system could develop. This step gave additional attention to the human side of the tensions.

Aim: explore how roles and trust between the ground handler and the system could be shaped.

Together, the steps engaged all five identified tensions. The session ran through all phases as planned, with active engagement from all participants. The concept development generated particularly rich discussion, producing concept ideas alongside the operational reasoning behind them. Removing the constraints of the current operation through the speculative case lowered the threshold for non-designer participants to engage with the future system more than expected. Translating these into a concrete workflow proved harder and required facilitation, but the clarifying questions asked during the session provided enough detail to complete the translation afterwards.

Figure 6.2: Impressions of the co-creation workshop

6.2. Analysis of the co-creation workshop

The workshop generated a rich set of conceptual directions and operational insights, sketches included in Appendix I. A thematic analysis was conducted to identify the patterns that emerged across the different concepts and discussions. Thematic analysis was selected because it offers a theoretically flexible method for identifying, analysing, and interpreting patterns of meaning across qualitative data [18, 2]. This flexibility made it suitable for combining different data types from the workshop, including visual concept material, participant discussions, and concept pitches. The analysis followed three steps: initial grouping of concepts by their operational logic, identification of recurring patterns, and thematic synthesis into desired outcomes.

Thematic analysis of the workshop surfaced four desired outcomes that together describe the shared ideal for the future 400 Hz connection (Figure 6.3). Each is summarised; the underlying themes are shown in the figure.

Desired outcomes

No physical demands
The desired outcome is a process that removes manual cable handling from the ground handler entirely, whether through cable support, autonomous handling, or eliminating the cable: *"something that can get close to the aircraft and lift the cables up itself"* (WP2).

Clear human-robot collaboration
Participants wanted the division of tasks explicitly defined: what the robot does autonomously, what the handler monitors or confirms, and when a human takes over: "*you are walking with your chocks and being followed by a robot, that I would find nerve-wracking*" (WP3).

Safe and predictable behaviour
The desired outcome is behaviour transparent and predictable enough for ground handlers to work safely alongside the robot, staying within stand boundaries and stopping when people or equipment are in its path. Familiarisation matters: WP6 compared it to cleaning robots in supermarkets, unfamiliar at first but quickly part of the environment.

Timely connection independent of planning
Participants envisioned a system that is present and ready at the stand when needed, regardless of staff availability. They saw on-gate deployment as most effective, though Schiphol noted it requires the highest investment: ``*from Schiphol's perspective it comes down to procurement: either you buy a hundred of them, or you buy six and make a smart planning*'' (WP1).

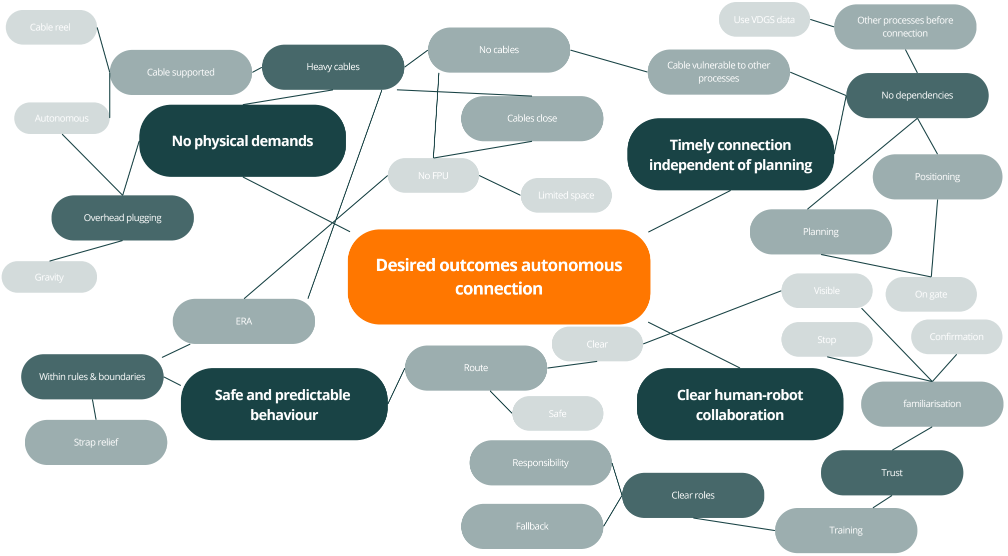


Figure 6.3: Four desired outcomes for the autonomous 400 Hz connection, derived from thematic analysis of the co-creation workshop

6.3. Choices in the tensions

This is the step the chapter has been building towards. Chapter 5 ended with five tensions, each requiring a design choice before a concept can take shape. The desired outcomes from the workshop directly inform these choices. T1 sets the directional choice for how the system is positioned within the operation, while T2–T5 define the conditions under which it can be implemented and trusted in practice. Table 6.2 presents the chosen direction for each tension; the full reasoning is given in Appendix J.

Table 6.2: Design choices for the five tensions, derived from the co-creation workshop. Each row gives the chosen direction and a representative quote; the full reasoning is provided in Appendix J.

#	Tension decision	Explanation	Quote
T1:	**Flexible deployment with stability ambition**	A flexible deployment model, designed to add stability rather than complexity. Every deployment option is judged on whether it structurally reduces the connection's vulnerability to planning dynamics, not just shifts the same problem from an absent handler to a mispositioned robot. Firmer on-gate integration can follow as experience and the business case grow.	*"It should be like the PCA unit, it could move ten metres, but not shift a hundred metres to the next stand" (WP3)*
T2:	**Gradual autonomy with explicit role division**	Full autonomy is the long-term goal, but during the transition each step must define both roles explicitly: what the robot does itself, what the handler monitors or confirms, and how the robot signals its actions. While people are still at the stand, it must stay physically predictable and interpretable; human oversight is reduced gradually as trust and reliability grow.	*"In fifteen years, I hope there is nobody on the platform during the arrival process because the air quality is bad" (WP4) / "You manually activate it, so there is still a form of control" (WP3)*
T3:	**Co-development as a condition for adoption**	The system must be developed together with the people who will use it. Decisions currently made at strategic level without operational input are a direct adoption risk, so co-development is treated as a condition for the concept, not an optional extra.	*"There should be much more consultation between Schiphol and the handlers at this level" (WP3)*
T4:	**Safe and workable behaviour**	Stop behaviour must be both reliable and workable: the robot stops when it genuinely cannot proceed safely, but not so often that handlers start bypassing it or losing trust in its ability to finish the task.	*"Like Roboxi it stops immediately if it can touch anything" (WP2)*
T5:	**Building on existing digital infrastructure**	The system builds on existing infrastructure, using the VDGS for task-level triggering and integrating with the ROS for broader coordination. It is not a standalone solution but an integrated component of the wider digital environment in the Autonomous Airside Operations programme.	*“As soon as the VDGS shows the aircraft type, the robot knows where to go" (WP6)*

6.4. The Adaptive North Star

The previous section produced five design choices, one per tension, but on their own they remain five separate decisions. To guide the development that follows, they need to be held together in a single direction. A design problem arises here: the future cannot be known in advance, so that direction cannot be fixed in full. Much of it can only be validated through pilots and further development. What is needed is therefore a guiding point that sets a clear direction without closing off the routes towards it.

This is where this research uses the strategy of a North Star, but makes it deliberately contradictory by calling it an Adaptive North Star. A North Star, like a fixed point on the horizon, draws its whole value from not moving; making it adaptive breaks that logic, a destination that is allowed to shift. It makes the direction explicitly open and carries the points still to be validated along with it. And it opens a new perspective: because the concept also states what remains open, committing to a direction becomes a lighter choice, a clear heading rather than a fixed endpoint that rules out every other future. This Adaptive North Star holds direction while keeping several futures open as operational experience, technology, and infrastructure develop.

Synthesising this direction is a design act of this research. It brings together the two inputs developed in this chapter, the desired outcomes and the tension choices. The participants shaped the individual choices, but combining them into one guiding direction, and deliberately framing it as adaptive, is the step taken here, and the basis for the development path that follows.

The Adaptive North Star for autonomous connection

The North Star for the autonomous 400 Hz connection is a self-driving, e-GPU robot that connects the aircraft to ground power without any human involvement. The robot is distributed across stands in a way that eliminates vulnerability to planning dynamics: it orchestrates its own availability and manages its charging schedule based on the flight schedule and grid conditions. It detects the aircraft type via the VDGS, navigates to the connection point, deploys its integrated chocks, opens the panel autonomously, and plugs in the connector. Where ground handlers remain involved during the transition, their role is explicit: they know exactly what the robot does and when they are expected to act.

The four design choices below give this vision its concrete form, grounded in the concepts and reasoning that participants developed during the co-creation workshop

No cables, battery-powered robot
Participants saw the cables and FPU island as a core problem, obstructive, often damaged, and physically demanding. Rather than improving cable handling, the vision eliminates it: a robot that carries its own power supply removes both the cables and the FPU island, frees up space at the stand, and avoids the ERA-driven distance between island and connection point. Given the rapid development of battery technology, a robot operating independently between flights is increasingly feasible. This removes physical demands and makes flexible deployment simpler (T1).

Chocks integrated into the robot
The connection point sits close to the nose gear, where chocks are also placed. If the goal is to remove human dependencies from the connection, the preceding steps, including chocking, must be covered too. Integrating chocks into the robot reduces the dependency chain by consolidating these preceding tasks into the system itself (T5).

VDGS integration and system coordination
To connect autonomously, the robot needs to know which aircraft type has arrived and where the connection point is. The VDGS already provides this and is active at every wide-body stand, making it the best-suited trigger. At the coordination level, a central orchestration system such as ROS manages the robot's availability across stands, schedules its charging around the flight schedule, and gives both Schiphol and ground handlers visibility over where it is and what it is doing (T2, T5).

Transparent status communication
The robot must also communicate directly with the ground handler at the stand. It signals its current state and intended next action through clear physical signals, so handlers know when to act and when to step back. This supports clear human-robot collaboration and keeps the role division explicit at every development step (T2).

Implications for development:

Because the Adaptive North Star sets a direction while deliberately leaving open what cannot yet be fixed, it cannot be reached in a single step. It calls for a development that advances towards the direction in stages, validating the open points as operational experience, technology, and infrastructure mature. The next chapter sets this out in a roadmap.

Chapter 7 | Roadmap and Concept

The Adaptive North Star sets the direction for the autonomous 400 Hz connection, but it describes a destination, not a way to get there. This chapter provides those steps: it first makes the Horizon 3 concept concrete, then constructs the development path back to the current operation, and finally sets out the requirements the system must meet along the way.

7. Roadmap and Concept

7.1. Operational concept of Horizon 3

Chapter 6 ended with the Adaptive North Star. Before the development path towards it can be constructed, its endpoint must be made concrete. That endpoint is the fully autonomous operational concept the roadmap works back from (Section 7.3). This section translates the Adaptive North Star into this concept: a self-driving, e-GPU robot that connects the aircraft where no ground handler can be present on time. The initial problem it needs to solve; make the connection there where no ground handlers are available. The concept consists of a visual representation, an operational workflow, and the operational requirements (These follow once the roadmap has defined the horizons in which each requirement is addressed (Section 7.4).)

Concept visualisation

Figure 7.1 visualises the operational concept. This is a representation, not a fixed design: its purpose is to make autonomous 400 Hz availability tangible and to give the workflow and requirements that follow a shared reference to build on.

Figure 7.1: Directional visualisation of the autonomous 400 Hz connection concept for Horizon 3. Not a final technical design, but a guiding image for the workflow and requirements that follow. Image generated with the assistance of ChatGPT and Vizcom.

Operational workflow of the concept

Figure 7.2 presents the operational concept as a service blueprint, positioning it within the inbound operation by making its integration with the surrounding processes and systems explicit. It follows the same five phases as the current workflow (standby, trigger, approach, connection, and engine shutdown), but using the adapted blueprinting approach for robots and humans introduced in Section 4.3 and maps them across four actors: the robot, the operator, the response team, and the system layer. These lanes show what the robot does, what the operator monitors, when the response team is activated, and how the surrounding system enables the process, making the dependencies between actors and systems visible in a single overview. An interactive version is available here (click).

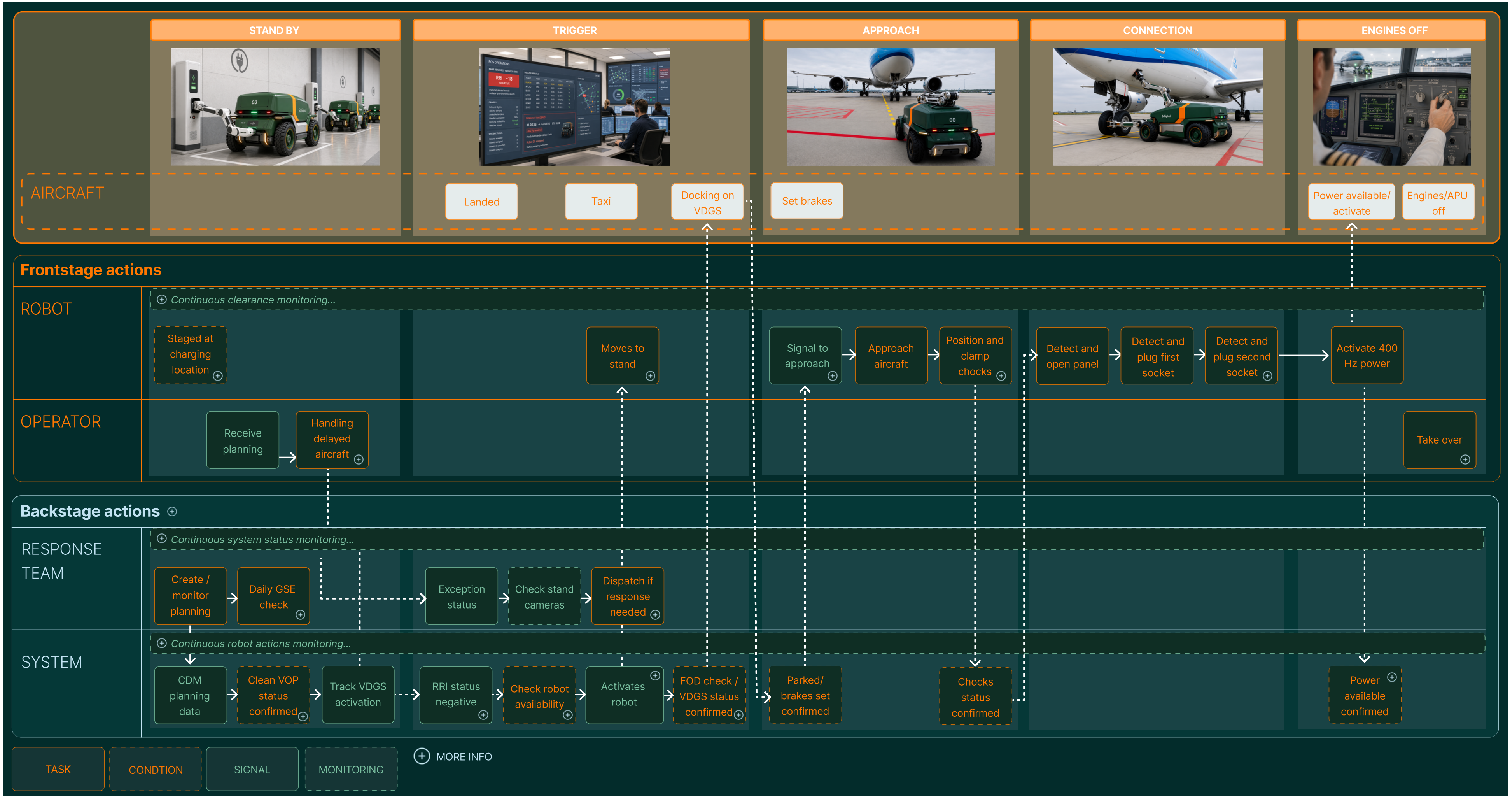


Figure 7.2: Horizon 3 operational workflow for autonomous 400 Hz connection, showing the coordinated sequence from standby to engine shutdown across the aircraft process, robot execution, operator supervision, response team support, and system orchestration

7.2. Method: Horizon-based development model

The Adaptive North Star describes the preferred future for the autonomous 400 Hz connection the operational concept is based on. This section describes the roadmap towards this concept. This development path is constructed through backcasting. Unlike forecasting, which extrapolates from current trends to predict what is likely, backcasting starts from a desired future and reasons backwards to determine what must happen for that future to be reached [61]. The question is not what will probably happen, but what steps are needed to arrive at a future that has been deliberately chosen [46]. This mirrors the speculative logic set out in Section 3.3, where design works back from a preferred ideal.

As shown in the previous chapters, the autonomous connection cannot be implemented as a single technical intervention; the challenge lies in embedding it within the interdependent inbound operation. The path is therefore structured as a sequence of horizons, each building on the operational experience of the one before. To position these horizons within a broader transformation logic, the roadmap draws on the Three Horizons model [22, 83]. Developed as a foresight tool, it distinguishes three patterns of change that coexist in a transition: the first horizon is the current dominant system being gradually phased out, the third is the fundamentally renewed system that replaces it, and the second is the transitional space of experiments that bridges the two. In this roadmap, Horizon 0 corresponds to the first, validating and strengthening the current situation; Horizons 1 and 2 form the transitional space in which the system is gradually introduced; and Horizon 3 represents the renewed operational reality of autonomous availability (Figure 7.3). Combining backcasting with the Three Horizons model in this way is supported by foresight literature on methodological mix [59, 46].

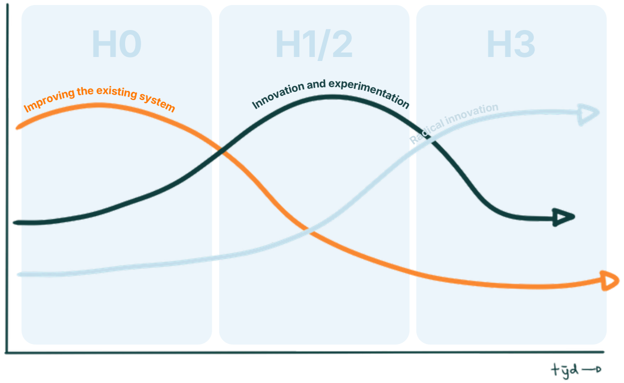


Figure 7.3: The Three Horizons model, distinguishing between improving the current dominant system, an experimental transition space, and a fundamentally renewed operational reality. In this roadmap, Horizon 0 corresponds to the first horizon, Horizons 1 and 2 to the second, and Horizon 3 to the third [88]

The four horizons

Each horizon identifies what must be learned, decided, and validated before the next can responsibly be taken: this is where the adaptive character of the North Star enters the roadmap. It organises the path around learning rather than time, defining not when full automation is achieved but what must be validated before each step. The path is divided into four horizons:

Horizon 0: Current situation - problem validation
Establish the operational foundation for autonomous connection development by quantifying the impact of planning dynamics on delayed connection, while strengthening the current manual process where possible.

Horizon 1: Controlled pilot
Develop the autonomous connection system, designed from the start for future dynamic deployment so that it brings stability, and test whether it can perform the task safely and reliably under controlled conditions before operational integration is attempted.

Horizon 2: Operational introduction
Introduce the system into selected operational contexts. The goal is to demonstrate that the system can function within the real operational environment and earn the trust needed for broader deployment.

Horizon 3: Autonomous availability
Represent the renewed operational model: the system moves autonomously to where a ground handler cannot be present on time, deployed through orchestration logic that coordinates availability across multiple stands.

The seven dimensions

Each horizon is described through seven consistent dimensions, derived from the tension choices made in Chapter 6. Together they ensure that the findings from the previous chapters converge in the roadmap and that autonomous 400 Hz connection is treated as a socio-technical development process in which the system, workflow, human role and organisational conditions evolve together.

- *Goal* defines the central development objective of each horizon, clarifying what must be learned or validated before the next step can responsibly be taken. This dimension is grounded in the Three Horizons model.
- *System capabilities* describe what the robot must be able to do in each horizon, shaped by T4, which concerns the performance and margins required for safe and workable autonomous connection. This dimension draws on the operational context from Chapter 2, the human-robot capability comparison and expected evolution in Section 3.2, and the current workflow from Chapter 4.
- *Orchestration* defines how the system is triggered, sequenced and coordinated within the inbound workflow, shaped by T5, which concerns the dependency on existing digital infrastructure. This dimension draws on the current workflow phases from Chapter 4 and the digital coordination infrastructure described in Chapter 2.
- *Human role* defines what ground handlers, safety operators, control room operators and response teams execute, monitor, confirm or take over in each horizon, shaped by T2, which concerns the balance between autonomy and human control. This dimension draws on the LORA framework introduced in Section 3.2 and on lessons from a current automation pilot at Schiphol described in Section 2.1
- Adoption and co-development defines how the user must be involved in each horizon, shaped by T3. This dimension draws on the user-centred design approach in Section 3.3, the conditions for successful adoption in Section 3.2, and the co-creation process in Chapter 6.
- *Development activities* bring together the preceding dimensions into concrete actions for each horizon.
- *Validation points* define what must be learned and confirmed before the next horizon can responsibly begin. This is where the adaptive character of the North Star enters the roadmap: rather than fixing each step to a date, the path is organised around what still has to be validated, and those points stay explicitly open until more operational experience, technology, or infrastructure allow decisions to be made.

7.3. Roadmap for autonomous 400 Hz connection

Reasoning logic: working back from Horizon 3

The Adaptive North Star gives the roadmap direction and Horizon 3, the operational concept introduced in section 7.1, is built on that direction. Following the backcasting logic, Horizon 3 is the starting point for reasoning: the roadmap works backwards from it to Horizon 0, determining at each step what must be in place for the next. It is presented in chronological order from H0 to H3, but the underlying logic runs in the opposite direction (Figure 7.4)

Figure 7.4: Backcasting reasoning logic: Adaptive North Star gives direction for Horizon 3 which functions as starting point for the roadmap

Roadmap overview

The full development path is brought together in the interactive roadmap (Figure 7.5). The Adaptive North Star sits at the top as the direction worked back from, and the four horizons (H0-H3) are laid out beneath it. Each horizon shows the tasks to be done in that horizon, divided by dimension. The Explore this horizon link opens a detail page with the full explanation per dimension, the development activities, the validation points, and the main bottlenecks for that phase. The validation points move through three states: to validate, refine, and confirmed (Figure 7.6). This reinforces that progress is organised around learning milestones rather than a fixed timeline. Following feedback, the roadmap was refined; the feedback and refinements are detailed in Appendix K.

The interactive version can be accessed through the following link.

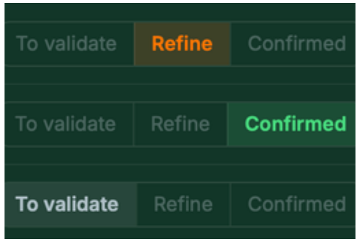
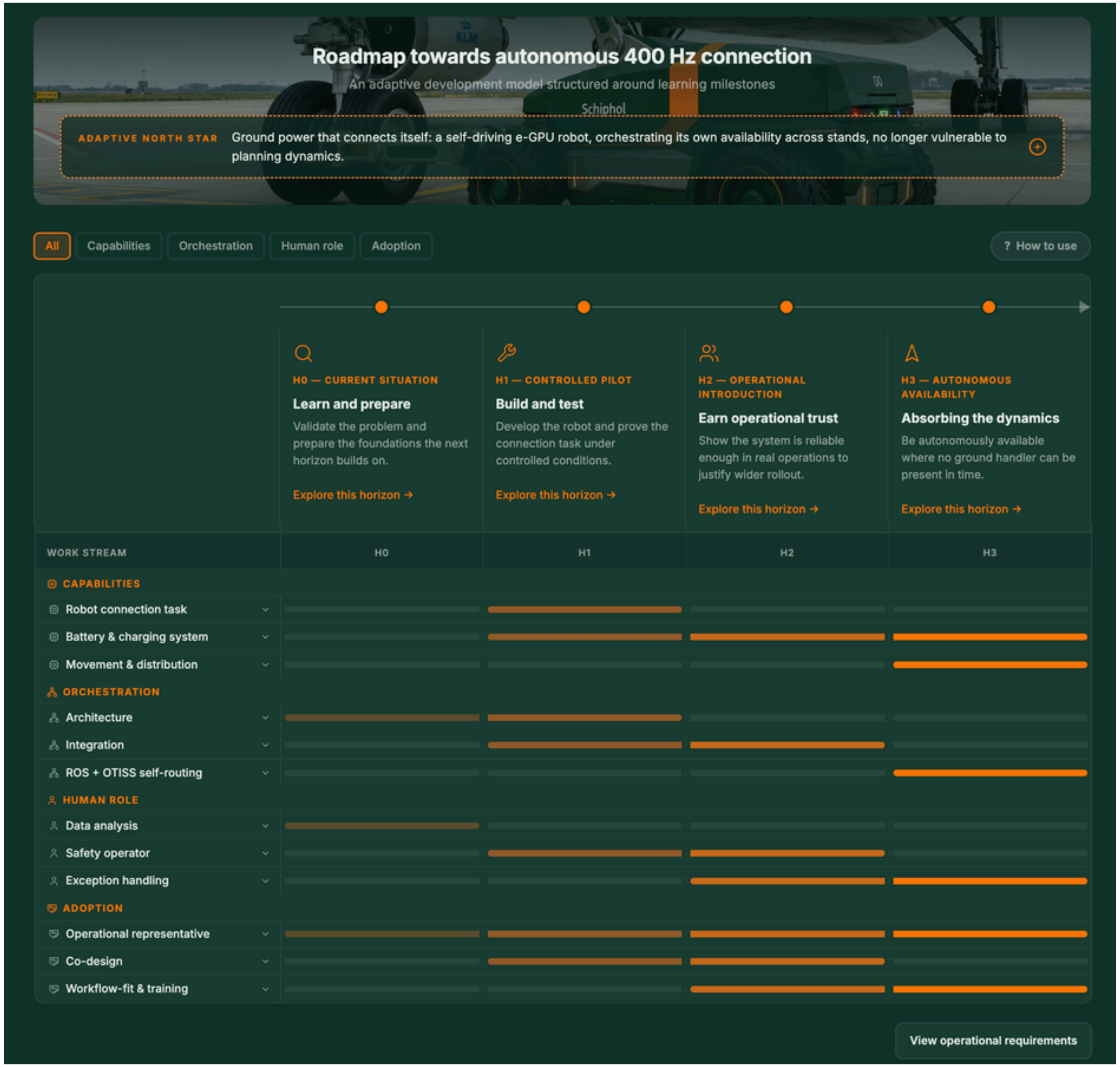


Figure 7.6. The three states for the validation points in the roadmap: to validate, refine, and confirmed.



Roadmap towards autonomous 400 Hz connection

An adaptive development model structured around learning milestones

ADAPTIVE NORTH STAR Ground power that connects itself: a self-driving e-GPU robot, orchestrating its own availability across stands, no longer vulnerable to planning dynamics.

H0 — CURRENT SITUATION
Learn and prepare
Validate the problem and prepare the foundations the next horizon builds on.
Explore this horizon →

H1 — CONTROLLED PILOT
Build and test
Develop the robot and prove the connection task under controlled conditions.
Explore this horizon →

H2 — OPERATIONAL INTRODUCTION
Earn operational trust
Show the system is reliable enough in real operations to justify wider rollout.
Explore this horizon →

H3 — AUTONOMOUS AVAILABILITY
Absorbing the dynamics
Be autonomously available where no ground handler can be present in time.
Explore this horizon →

Figure 7.5: Interactive horizon-based roadmap for autonomous 400 Hz connection, combining the four horizons (H0–H3) into a single overview that works backward from the Adaptive North Star.

Horizon 0 - Current situation and problem validation

Goal

This horizon has three aims: validating the relevance of autonomous connection, preparing the systems on which the later horizons build, and improving the existing manual process where possible. Schiphol's operational data shows that approximately 10% of arriving flights experience docking issues, but this combines three distinct causes: work culture and mentality, last-minute planning changes, and misplaced ground support equipment (Section 4.4). The relative contribution of each is not yet known. Of these, autonomous connection specifically addresses planning dynamics, as it operates independently of human availability. Establishing how much of the 10% this accounts for determines how much of the problem an autonomous system could realistically remove, and whether that share justifies the investment. Schiphol is aware that this share is still unknown and has already begun gathering the data, so the task here is not to collect new data but to interpret it specifically for this question. In parallel, this horizon begins building the orchestration architecture on which the later horizons depend, and draws lessons from existing pilots that address the same availability problem.

System capabilities

No robot is deployed in this horizon; the primary tool is the data infrastructure already in place. The DeepTurn cameras and the Ramp Readiness Indicator (RRI) already collect stand-level data, which this horizon uses to quantify how much of the delayed connection is caused by planning dynamics. Duration matters as much as frequency here: a cause resolved within seconds has far less impact on emissions and engine runtime than one that structurally delays connection by several minutes. A prerequisite for reliable analysis is a shared measurement standard, which Schiphol does not yet have. Currently, its systems register connection time from the moment the aircraft crosses the stopping line, which does not align with the operational rule that the connection must be established within five minutes of the aircraft coming to a standstill. Without a clear and agreed standard, data findings remain contestable, as stakeholders can always point to measurement inconsistencies.

In parallel, short-term interventions address the two causes that autonomous connection cannot solve, building on work Schiphol has already begun. For misplaced GSE and work culture, Schiphol is developing a clean VOP system: DeepTurn cameras linked to arrival schedules detect incorrectly positioned equipment well before the planned arrival, triggering an alert so the obstruction can be resolved in time. Alongside this, Authority officers are being introduced to act on these signals and address ground handling parties directly when stands are not cleared on time, which also strengthens work culture: when non-compliance is visible and specific parties are addressed, accountability and the motivation to prepare stands on time increase. This horizon's contribution is to continue and reinforce these measures rather than introduce them.

Physical workload was identified as the most directly felt problem by ground handlers in Wide-Body operations, consistently experienced as one of the most negative aspects of the current inbound task. The autonomous system will only address this once the connection task is structurally deployed. In the meantime, lighter cables and a cable support trolley are already being investigated as low-complexity improvements that can reduce the physical burden. Schiphol should continue and accelerate these efforts in this horizon, as they address a real and immediate user need independently of the autonomous development path.

Orchestration

No robot orchestration is required in this horizon; the focus is on using Schiphol's existing data infrastructure (DeepTurn, RRI, Wilbur) to validate the problem and inform the development direction. The marshal team pilot is the key focus here: because a team is dispatched when no ground handler is present on time, it reveals how far in advance this need becomes known and whether acting on that signal brings stability. This trigger logic is the direct predecessor of the trigger the autonomous robot depends on in later horizons.

What this horizon adds is the foundation for it. An overarching orchestration architecture must be set up that gives Schiphol insight into ground handler planning and predicts gaps using DeepTurn and ROS, and it must be tested against the marshal team deployment logic. In parallel, ROS must be extended to integrate the relevant data inputs, including DeepTurn camera feeds, VDGS signals, and arrival schedule data, so that it can support task sequence logic when the robot is introduced in Horizon 1. Establishing and testing these data connections ensures the orchestration layer is ready for autonomous deployment.

Human role

In this horizon, no human-robot role division exists. All operational tasks remain fully human-executed. The human role is therefore analytical. Schiphol's operation and innovation teams analyse the stand-level data and draw lessons from the marshal team pilot. Ground handlers contribute the operational perspective: their input is essential for interpreting what the data reveals in practice and for ensuring the problem statement is recognised at the level of those who work at the stand. Their involvement is equally necessary for exploring work culture interventions, as effective measures require understanding what drives behaviour at the stand.

Adoption and co-development

In this horizon, adoption begins before the robot is developed. The co-creation workshop conducted in this research showed that engaging operational stakeholders in early-stage discussions, rather than limiting involvement to business and strategic conversations, is experienced as valuable and builds the shared understanding that later adoption depends on.

Involvement must be sustained throughout development from this horizon onwards. A concrete way to structure this is by including an operational representative in the core development team from the start, so that practical knowledge informs decisions continuously rather than only at designated review moments. At key milestones or when significant design decisions are made, additional ground handlers should be consulted to validate that the direction still aligns with operational reality.

Development activities

- Analyse DeepTurn data: frequency and operational impact of each cause of delayed connection.
- Establish a shared measurement standard, aligned with the five-minute rule from standstill.
- Evaluate the marshal team pilot: advance-notice window and effect of last-minute interventions on timing.
- Investigate work-culture (intrinsic motivation) interventions with ground handler input.
- Continue short-term workload measures: lighter cables, cable support trolley.
- Extend the clean-VOP GSE-detection trigger (DeepTurn linked to arrival schedules).
- Investigate and set up the overarching orchestration architecture, integrating DeepTurn, VDGS signals, arrival schedule data and ROS; test against marshal team logic.
- Run structured sessions with ground handlers to validate the problem definition from an operational perspective.

Validation points

- The contribution of planning dynamics to delayed connection is quantified and sufficiently large to justify investment in an autonomous connection system.
- The operational logic developed for marshal team deployment provides a viable basis for the autonomous system's trigger mechanism.
- The overarching orchestration architecture integrating DeepTurn, VDGS, arrival schedule data and ROS is established and suited.
- An operational representative is actively involved in the development team.

Horizon 1 - Controlled pilot

Goal

This horizon translates the operational concept developed in this research into a physical system that can be tested in practice. Wide-body handling is the initial operational context. It is physically demanding, clearly bounded, and embedded in a relatively structured digital environment through the VDGS. The operational concept and requirements defined later in this chapter (Section 7.4) provide the foundation for a technology developer to design and build the robot.

Although the pilot is controlled, the system should not be developed as a static single-stand automation solution. From the start, the robot must be designed as a future dynamic operational asset that can eventually operate in a shared apron environment, interact safely with surrounding vehicles, and absorb planning dynamics and last-minute changes in the inbound workflow (based on learning from H0). This prevents the pilot from optimising only for the physical plug-in task and ensures that the technical architecture remains scalable towards wider and more flexible deployment in later horizons.

In parallel with technical development, a number of preconditions must be addressed. Certification trajectories with Boeing and Airbus must be initiated, as any system that physically interfaces with an aircraft requires manufacturer approval. Airlines must be consulted about the use of a robotic system on their aircraft. Organisational responsibilities must also be clarified: given that Schiphol intends to own the system while ground handlers remain the executing party at the stand, it must be established where liability lies when the system fails or causes damage.

System capabilities

The core of this horizon is the design and development of a battery-powered robot with an integrated arm capable of autonomously executing the 400 Hz connection. Key technical components include the battery and power management system, the connection arm, and an on-stand charging solution that allows the robot to recharge between flights.

Besides the physical connection task, the robot must already be developed with future dynamic deployment in mind. This includes the ability to position itself accurately around different aircraft types, to detect and respond to surrounding vehicles, GSE and obstacles, and to operate safely in a shared apron environment. In H1, these capabilities are not yet tested as full flexible deployment, but they are treated as technical development requirements from the start. The system architecture should therefore allow later expansion towards dynamic positioning, stand-to-stand deployment, and operational use.

A central development question is determining the reliable trigger for the robot to cross the ERA boundary and approach the aircraft. Two candidate trigger sources must be evaluated: the anti-collision lights signal routed through DeepTurn and ROS, and the VDGS signal routed through ROS. In the current operation, anti-collision lights off signals that the stand is safe to enter. However, if aircraft increasingly dock without APU use and on a single engine, the anti-collision lights are no longer a reliable indicator. In that case, an alternative trigger such as a brakes-on signal from the VDGS must be used. Determining which trigger is appropriate under which operational conditions is a key learning objective of this horizon.

Aircraft type recognition and precise connection point localisation are also core capabilities to be developed. The VDGS already links aircraft type to stand position, making this data available. This must be translated into a format the robot can use for positioning and approach. Aircraft-type-specific connection point location data must be coupled to the VDGS system so that the robot can determine the precise target location for each inbound flight.

A further design question is whether chock placement should be integrated into the robot. The connection point is located close to the aircraft nose gear where chocks are also placed. Integrating chocks would reduce the dependency chain before the robot can initiate the connection.

The pilot is structured in phases and takes place outside of Schiphol's operational environment. Initial testing takes place on a dedicated mock-up or stationary test aircraft at a regional airport. Once sufficient confidence has been built, testing progresses to a real aircraft under realistic but controlled conditions, still at a regional airport, accumulating sufficient pilot hours before any introduction into Schiphol's operation.

Orchestration

In this horizon, orchestration begins with minimal system integration and progressively shifts towards remote activation. The development progresses through four stages. First, the robot is stationary and only the connection task itself is tested (opening the panel, positioning the arm, and plugging in the connector) without any movement or activation logic. This builds directly on the Proof of Technology. Second, the robot is remotely driven from a short distance by an operator physically present at the stand. Third, the robot integrates with

VDGS data on aircraft type and stand composition to execute the approach route and connection autonomously while a human operator remains present at the stand for supervision. Fourth, supervision shifts to the control room: the robot operates autonomously at the stand while the control room monitors its status and can intervene when needed.

ROS is activated progressively across these stages. Initially it receives VDGS data for aircraft type recognition and approach route logic. As the system matures, ROS also receives the trigger signal, confirms preconditions, and activates the robot. In the final stage, the full task sequence logic is tested through ROS. The status signals the robot communicates at the stand and the information feed to the control room must be developed and tested throughout this progression, in close collaboration with ground handlers.

Human role

The human role follows the four orchestration stages described above, reflecting the gradual shift towards autonomy: the safety operator moves from manually initiating the task at the stand, to remotely driving the robot, to supervising autonomous execution at the stand, and finally to monitoring from the control room.

In parallel, this horizon must investigate the signals needed for hybrid situations in which a ground handler is unexpectedly present while the robot is active. Although the robot is deployed when no handler is available on time, in practice one may arrive while it is already executing. The ground handler must clearly understand when the robot is active, what it is doing, and when they can safely proceed or should intervene. Defining and testing these signals with ground handlers is a core deliverable of this horizon. Before the robot transitions to an operational setting, the training programme and rollout must be designed.

Adoption and co-development

Ground handlers must be involved from the earliest test phases, not only in the final pilots before operational deployment. Involving users when core design choices are still being made ensures that the system is shaped by operational reality and that ground handlers recognise their input in the outcome.

During the pilot phases, structured feedback from ground handlers must be collected and acted upon. This means evaluating not only whether the robot performs the task correctly, but also whether operators experience it as workable, whether they understand what it is doing, and whether they see its added value in practice. Their practical experience is essential for ensuring that the robot can function in more realistic operational situations.

Development activities

- Select a technology developer on the established requirements; start development of the battery-powered robot.
- Develop and test the battery system: capacity, charging-cycle management, on-stand infrastructure.
- Build and test the stationary connection task on a mock-up/test aircraft at a regional airport.
- Integrate VDGS data for type recognition and connection-point localisation; develop approach-route logic.
- Evaluate trigger sources and determine which is reliable and timely enough under current and evolving inbound operational conditions.
- Progressively activate ROS integration: starting with VDGS data for aircraft type recognition and approach route logic, then trigger signal and precondition confirmation, and finally full task sequence logic.
- Initiate certification trajectories with Boeing and Airbus and begin consultations with airlines.
- Clarify organisational responsibilities and liability in the event of system failure or damage.
- Develop and test the stand status signals and control-room feed, with ground handlers.
- Design the training programme and rollout plan.
- Actively involve ground handlers throughout the pilot phases; collect structured feedback on workability, clarity, added value

Validation points

- The robot can reliably execute the full connection task autonomously in a bounded environment, progressing through all four stages of the role division.
- The trigger logic is validated and reliable under current and evolving inbound operational conditions.
- Certification trajectories with Boeing and Airbus are initiated and no blocking issues have been identified that prevent operational introduction.
- Organisational responsibilities and liability are clearly defined.
- Ground handlers understand and accept the system well enough to work alongside it in an operational setting.
- The training programme and rollout plan are developed and validated with ground handlers.

Horizon 2 - Operational introduction

Goal

This horizon marks the transition from controlled pilot to real operational deployment, structured in two phases. First, the system is introduced at a regional airport in a live but bounded operational context: real aircraft, real turnaround conditions, but without the full complexity of Schiphol's airside. Only when the system has demonstrated sufficient reliability in this setting does it transfer to a carefully selected set of Wide-Body stands at Schiphol.

The focus shifts from technical feasibility to operational reliability, the system must prove that it can function within the inbound workflow, interact with ground handlers and a response team, and gradually reduce the need for active supervision. By the end of this horizon, the system has earned sufficient operational trust to justify deployment on additional stands at Schiphol, and the organisation has the data, experience and role clarity needed to move towards autonomous orchestration.

System capabilities

In this horizon, the robot is permanently stationed at a selected set of stands and its operational purpose is to execute the 400 Hz connection. The complexity of dynamic positioning and flexible deployment across the airside is excluded: by isolating the connection task from the broader orchestration challenge, this horizon concentrates on validating the systems and triggers that autonomous connection depends on in a live environment.

The robot must function safely alongside other stand processes. The ERA constraints remain directly relevant: the robot must respect stand safety zones and respond to the presence of other equipment and staff. How the robot handles these situations in practice is a core learning objective of this horizon.

The battery system is used in a real operational environment for the first time. Performance, charging cycles, and availability must be actively monitored to understand whether the current charging strategy and infrastructure are sufficient under varying turnaround times and flight sequences. The lessons learned must result in a concrete charging strategy and infrastructure plan that supports reliable availability in Horizon 3.

Orchestration

The robot is triggered by ROS with input from the DeepTurn cameras, which holds the task-sequence overview and knows when the robot should act. Orchestration evolves across four stages. Initially, the trigger operates under operator approval, with a safety operator providing active on-stand oversight. As reliability is demonstrated, the robot activates autonomously while the safety operator remains present at the stand to monitor and intervene. On-stand presence is then replaced by a dispatched response team, and the trigger moves to control-room approval, where ROS proposes activation and a control-room operator confirms. Finally, the control room shifts from approval to monitoring and exception handling: the robot executes autonomously and the control room intervenes only when an alert is triggered. The Wilbur platform enables this progression: by bringing the relevant operational data streams into a single overview, it allows the control room to monitor multiple stands simultaneously without steering each robot.

Human role

The human role follows the four orchestration stages above, moving from on-stand approval, to on-stand monitoring without approval, to a dispatched response team replacing physical presence, to control-room exception handling. Two roles need explicit definition. The safety operator, present during the first two stages, requires clear training on what to observe, when to intervene, and under what conditions to stop the robot; their feedback must be systematically collected, as their experience provides valuable insight into the robot's signals and functioning. The response team, introduced once on-stand presence is no longer required, is a dedicated group dispatched when the system signals a problem or the control room identifies an issue via DeepTurn; its activation conditions and required response time must be explicitly defined and tested.

Adoption and co-development

This horizon is the first time the robot operates in the real environment alongside ground handlers who may not have been directly involved in the development process. Broader deployment unavoidably introduces ground handlers who encounter the system for the first time, making adoption more demanding than in the controlled pilot phase.

Compatibility with the existing workflow is a critical condition. A particularly important threshold is task execution speed: ground handlers have indicated that they will simply take over the task manually if the robot is too slow. A system that is structurally bypassed does not deliver operational value and undermines the trust this horizon depends on building.

Role clarity is equally important. Ground handlers must understand precisely what the robot does, what they are responsible for, and when they are expected to act. Training must cover not only operational procedures but also the signals the robot communicates: its current status, intended next action, and position at the stand. Training must be developed in close collaboration with ground handlers and updated as the role division evolves across the four stages of this horizon.

Development activities

- Introduce the system at a regional airport; validate under real conditions before transferring to Schiphol.
- Integrate with ROS (trigger-based activation) and Wilbur (stand monitoring) at Schiphol.
- Test and validate the trigger logic across the full range of operational conditions encountered at the selected stands.
- Test and iterate robot behaviour alongside other stand processes, equipment and personnel.
- Roll out charging infrastructure; monitor battery performance; refine the charging strategy for H3.
- Define and validate the criteria for progressing between the four oversight stages.
- Establish the response team as introduced in the human role: define activation conditions, required response times, and test deployment in practice.
- Collect and act on feedback from safety operators and ground handlers.
- Analyse data for the optimal robot-to-stand ratio and required advance notice for H3.
- Building on H0, assess whether ground handler planning data can feed delay prediction and proactive dispatch in H3.

Validation points

- The system operates reliably without active supervision at the stand, having demonstrated sufficient performance across all four oversight stages.
- The robot functions within daily operations without disrupting surrounding stand processes.
- The role division between ground handler, robot, control room and response team is understood and accepted by all parties.
- The charging infrastructure and response team capacity are sufficient to support deployment at a significantly larger number of stands.
- A concrete deployment model for Horizon 3 is defined, including robot-to-stand ratio and required advance notice for reliable dispatch.
- The operational performance data confirms that autonomous connection can structurally reduce the planning dynamics problem identified in this research.

Horizon 3 - Autonomous availability

Goal

This horizon deploys the autonomous connection system for the purpose it was ultimately designed for: being available where ground handlers cannot be present on time, directly addressing the planning dynamics problem validated in Horizon 0. The previous horizons demonstrated that the robot can execute the connection task reliably and that the operational environment can work with it. Horizon 3 introduces the capability that was deliberately excluded until now: autonomous movement beyond the fixed stand.

This capability is not introduced in a single step. The robot progressively moves from being steered remotely by a control room operator, to receiving routing instructions while driving autonomously, to fully self-directed movement integrated with ROS and OTISS. The central challenge of this horizon is therefore not the connection task itself, but building the orchestration around it step by step: how the robot is dispatched, how it learns to move safely through the airside, and how competing demands are prioritised as more stands are covered.

The deployment logic builds directly on the learnings from the marshal team analysis in Horizon 0 and the operational experience accumulated in Horizons 1 and 2.

System capabilities

Robot distribution is a key design question in this horizon: how robots are distributed across the airside and where charging infrastructure should be located to ensure timely arrival at the target stand. The right approach depends on data from previous horizons on where, when and how often the robot would have been needed, and is determined through the deployment model developed in Horizon 2. The dispatch logic integrates with ROS, connects to inbound planning data, and advises on where the robot is likely to be needed so it can be positioned proactively. Movement between stands must also be organised, including whether the robot operates on dedicated routes or shares space with manual ground support vehicles; how this movement is built up is set out under Orchestration.

A further condition is that preceding tasks, such as engine shutdown, must no longer depend on human presence before the connection can begin, so the robot can deliver timely connection independently.

Finally, charging becomes intelligent rather than fixed: ROS applies fast charging when the robot is needed soon and slow charging in low-demand periods, shifting towards lower grid load or greater renewable supply based on the flight schedule and grid conditions, contributing to Schiphol's sustainability ambitions.

Orchestration

The orchestration backbone of this horizon is the progressive integration between ROS and OTISS. In the first phase, ROS provides planning advice to a control-room operator who manually dispatches and steers the robot with OTISS. In the second phase, the operator uses ROS data to issue routing instructions to an autonomously driving robot, with human judgement still in the loop for dispatch. In the third phase, ROS and OTISS are fully integrated: ROS determines when and where connection is needed, OTISS translates this into traffic decisions (route selection, intersection priority, detours and charging allocation), and the robot executes without human input for individual movements.

The dispatch communication interface between Schiphol's planning systems and ground handling parties' systems must also be developed here, serving two purposes: making dispatch decisions automatically visible to the relevant teams, and providing proactive advice on where and when the robot is likely to be needed, so it is positioned ahead of time rather than reacting to confirmed delays.

Human role

The connection task enters this horizon at the autonomy level reached at the end of Horizon 2: the robot executes autonomously, the control room monitors, and the response team is deployed on alert. This model scales as more robots run simultaneously. The new role development concerns autonomous movement, and follows the three orchestration phases above: the operator moves from actively steering the robot, to issuing routing instructions to an autonomously driving robot, to exception handling only, intervening when the system signals a situation it cannot resolve. A critical aspect concerns handover situations. The robot is dispatched when planning data indicates a ground handler will not be present on time, but a handler may arrive while it is already executing. The handover protocols first explored in Horizon 1 are completed here: how the team is informed of dispatch, when they take over, and under what conditions they intervene, developed with ground handlers and embedded in both the training programme and the operational communication systems.

Adoption and co-development
The first challenge concerns communication around dispatch and handover. When the robot is sent to a stand because a ground handler is not expected on time, the handler must know this. Without clear communication, a handler who is running late may rush to the stand unnecessarily, or conversely assume the robot is handling the task when it is not. A reliable and timely communication mechanism must be developed, integrated into the planning systems used by ground handling parties.

A second challenge concerns autonomous movement. Ground handlers will now encounter a moving robot not only at the stand but also between gates. Transparency about how the robot moves, what it does when it encounters an obstacle, and how it signals its intentions must be part of the training programme.

Development activities
- Develop and validate autonomous movement across three phases: control room steering based on ROS planning advice, operator-directed routing of an autonomously driving robot, and fully integrated self-directed navigation via ROS and OTISS.
- Integrate ROS and OTISS progressively and validate their combined performance under real operational conditions.
- Develop the dispatch communication interface, including proactive planning advice on robot positioning, and create an integrated system with ground handling operational systems.
- Determine deployment zone, robot distribution and charging infrastructure layout based on the deployment model from Horizon 2, and implement charging locations with Schiphol Infra.
- Define and implement handover protocols for hybrid robot-and-handler situations.
- Initiate certification for autonomous movement in mixed airside traffic, drawing on Schiphol's autonomous vehicle pilots.

Validation points
- The robot can navigate autonomously to any stand within the deployment zone, with the full ROS and OTISS integration operational and validated under real operational conditions.
- The robot arrives almost always at the stand before the aircraft connection must be made, confirming that the timing and dispatch threshold work in practice.
- Ground handlers are informed of robot dispatch through their own planning systems and confirm that the communication is timely and clear.
- Operational data shows a measurable reduction in docking issues at stands covered by the autonomous system compared to the baseline established in Horizon 0.

7.4. List of requirements

Table 7.1 presents the operational requirements for the autonomous 400 Hz connection. In line with the scope of this research, they concern how the system integrates into the inbound operation: what it must do to function safely and reliably alongside the surrounding processes, actors, and systems at the stand. They are not final technical specifications, but requirements that guide development and validation across the horizons. Each requirement is linked to a MoSCoW priority and a horizon in which it should be addressed.

Table 7.1: Operational requirements for the autonomous 400 Hz connection system, structured by workflow phase, MoSCoW priority and development horizon

Operational requirement	MoSCoW	Horizon
General		
Robot is able to operate alongside ground handlers and GSE without causing disruption	Must	H1/H2/H3
Robot is certified to connect to aircraft, including Boeing/Airbus approval	Must	H1/H2/H3
Robot includes emergency stop and manual override	Must	H1/H2/H3
The system minimises manual cable handling	Should	H1/H2/H3
Robot accounts for the limited space available at the airside and VOP in all operational positions	Should	H1/H2
In case of failure, the robot provides a visible and digital status signal to the responsible ground handler and ROS/Wilbur	Should	H1/H2
The robot operates under normal airside weather conditions, including snow, rain and wind	Should	H1/H2
Autonomous connection reduces the impact of planning dynamics and last-minute changes	Should	H3
The robot secures the aircraft in position as a functional replacement for manual chock placement before initiating the power connection	Could	H1/H2/H3

Operational requirement	MoSCoW	Horizon
Standby		
Robot is fully charged and operationally ready before aircraft arrival	Should	H2/H3
Robot has a defined home or charging position that does not obstruct other GSE or processes	Should	H2/H3
Robot deployment is based on a validated operational readiness signal, such as operator presence detection via DeepTurn/RRI and predictive planning	Should	H3
Robot is coupled to VDGS for VOP and aircraft type recognition	Could	H1/H2/H3
Trigger		
Robot is able to drive in a hybrid environment across the airside	Must	H3
The robot approach trigger is based on VDGS (brakes on) or anti-collision lights	Could	H2/H3
ROS planning tool checks robot availability and dispatches the robot to the VOP	Could	H3
Robot confirms that the trigger has been received and that the task has been initiated to ROS	Could	H2/H3
Trigger logic accounts for cases where the robot is already occupied at another VOP	Should	H3
Approach		
The robot only enters the aircraft stand area when FOD clearance, VDGS docking confirmation and chock placement have been confirmed	Must	H2/H3
Robot remains outside the ERA until the approach trigger is confirmed, covering a distance of 4.5-7.5 metres	Must	H2/H3

Operational requirement	MoSCoW	Horizon
Approach		
Robot stops immediately when it detects an unexpected obstacle	Must	H1/H2/H3
In case of a cable-based system, cables are pulled further than the connection point to avoid tension on the plug	Should	H1/H2/H3
Connection		
Robot is small enough to allow catering access at the first door	Must	H2/H3
Robot makes two plug connections for wide-body aircraft	Must	H1/H2/H3
Cable or connector is supported, equivalent to the current strap relief	Must	H2/H3
Once connected, the plug does not disconnect or fall out unintentionally	Must	H2/H3
System sends connection status to ROS	Could	H2/H3
Shutdown		
Robot clearly signals when the task is completed for human-robot role division	Should	H2/H3
Nearby ground handler is notified with a visible status when the robot task is complete and handover is possible	Should	H1/H2/H3
Digital status update is sent to Wilbur/ROS for turnaround oversight	Could	H2/H3

Chapter 8 | Discussion & Limitations

Integrating the autonomous connection meant fitting the system into the surrounding workflow and the developments still unfolding around it, deciding between the diverging interests of Schiphol and the ground handlers, and giving the development a concrete direction while accepting that the future operation cannot be fully specified in advance. The following sections reflect on what this meant.

8.1. Discussion

Integrating a concept into a live operation proved both insightful and challenging. Mapping the current situation was relatively straightforward; the difficulty lay in holding that picture together with where the operation is heading, including the innovations already planned that are reshaping the operation the autonomous connection must fit into. Even with a clear sense of where the system could fit within the operation, the main challenge was committing to a concept configuration: many options remained possible, and much could only be learned by testing what works in practice and what operators find workable. Listening closely to those on the organisational and operational side, and shaping the concept with their input, helped. It became more manageable once the concept no longer had to settle everything at once by creating the Adaptive North Star: a direction to which the operational findings could be attached. The following sections present the key learnings, the contributions, and the limitations.

Key Learnings

Principles give guidance, not a concept approach
A learning concerns the gap between what the literature was expected to offer and what it actually provided once technical feasibility had been established. The expectation going in was that it would give concrete handles for approaching an operational design process for automation. The principles in Chapter 3 proved valuable for guidance and direction, steering the approach towards a user-centred perspective and the current operation. But they said less about how to actually arrive at a concept for a specific operation. Reaching that concept, and gaining the operational insight it required, was something the research had to do with its own methods: service blueprinting to surface the workflow and the robot's integration into it, and co-design in a speculative form to reveal the desired outcomes for the future operation.

Diverse context: focus needed for the project
A learning concerns the diversity of operational contexts. Although the connection is a single technical task, the surrounding operation differs substantially across aircraft types, stand layouts, infrastructure, and routines, so no single concept fits all at once. This made clear that design decisions could not be taken in the abstract: without committing to one concrete context, every choice would stay conditional on which operation it applied to. Choosing a primary context was therefore a precondition for making decisions, setting the concrete conditions the concept could be developed and judged against.

Making stakeholder interests explicit enabled decisions
Autonomous connection must respond to several stakeholder interests at once, and these do not automatically align. Schiphol frames it around timely docking, emissions, and future-proof operations, while for the ground handlers its value lies in reducing physical workload and keeping the daily process workable, and even within each party priorities differ. Across the interviews and conversations these interests genuinely lay apart, which made the design challenging, but making the tensions explicit is what allowed a clear direction to be chosen for each.

Speculation opened up the user perspective
Another learning was how well speculative thinking worked to involve operational users. The expectation was that reasoning about an abstract, future system would be hard for participants who are not designers and work within the constraints of the daily operation. The opposite happened: by removing those constraints, they engaged more readily than anticipated, expressing what they actually wanted from the future connection rather than what is currently feasible.

The concept has to stay adaptive
The concept had to remain adaptive, because the future operation cannot yet be fully specified. Many configurations of autonomous 400 Hz connection are possible, and which one becomes appropriate depends on technical maturity, orchestration logic, operational data, infrastructure choices, governance and the experience gained from pilots. The concept could therefore not be framed as a fixed endpoint. The Adaptive North Star instead provides a shared preferred direction to which operational requirements can be attached, while the horizon-based roadmap structures the learning needed to move towards it. Framing the direction as adaptive opened a new perspective: because it makes explicit what still has to be validated, committing to it becomes a lighter choice. Its adaptivity is a deliberate response to the uncertainty under which the system must be developed.

Operational Contributions

Schiphol
The research turns a technically proven connection into a usable path towards operational integration. Where the Proof of Technology left the system's operational role undefined, Schiphol now has a concrete, operation-specific concept to develop further. This is the main contribution, made up of two parts.

A concept: the Horizon 3 operational concept, embedded in the operation through a service blueprint and supported by phased, prioritised requirements, makes the direction set by the Adaptive North Star concrete and grounds it in operational practice.

A path: the horizon-based roadmap makes explicit what still needs validation before each larger step, so the first moves are clear while the adaptive character stays visible.

Both rest on a single move: the divergence between Schiphol and the ground handlers was turned into explicit design choices through co-design, grounded in the specific Schiphol context.

Aviation industry
Although the concept was developed for Schiphol, the underlying context is not unique to it: many airports face the same combination of staff pressure and a connection task that has to fit a busy, interdependent stand operation. The concept is therefore partly transferable, though some elements are Schiphol-specific and would need adaptation. Three layers can be distinguished.

Transfers directly: the system is independent of current fixed electrification infrastructure. The robot carries its own power and works without the FPU, so it functions as a standalone system and could also suit smaller airports that lack fixed power infrastructure.

Might need adapting - the driving problem: at Schiphol, emission and air-quality pressure is what makes a staff shortage so critical, since every delayed connection means avoidable emissions, which is why punctual connection and predictive planning are central. At other airports where staff shortage is mainly a capacity problem without that pressure, the time-criticality falls away, and much of the concept's complexity (predictive planning, flexible deployment, ROS/OTISS orchestration) is no longer needed: a simpler, more static set-up would suffice.

Probably need adapting - the digital layer: the concept relies on the VDGS for aircraft recognition and on systems Schiphol already operates or is developing. This environment is not a given even within Schiphol: Narrow-Body stands lack the VDGS, and airports without this digital infrastructure would need to investigate how to provide the robot with data and control it.

Scientific Contributions

An adaptive form of direction: The research takes the strategy of a North Star but makes it deliberately contradictory: a North Star draws its whole value from not moving, and making it adaptive breaks that logic, turning it into a destination that is allowed to shift. It holds a shared direction while carrying the points still to be validated along with it. This opens a new perspective for designing under uncertainty: because the direction also states what remains open, committing to it becomes a lighter choice, a clear heading rather than a fixed endpoint that rules out every other future, a concept other contexts facing the same condition could draw on.

Methodological: a way to turn abstract automation principles into workflow-level design choices for a specific operation. Service blueprinting made the workflow, its dependencies and roles visible; speculative scenarios opened up thinking beyond the current operation; and co-design turned the tensions between Schiphol and the ground handlers into concrete decisions both parties accept. Where the literature gives principles but no method to apply them together, this shows one way to do it: reconciling strategic goals with operational concerns by making competing priorities explicit.

8.2. Limitations

Scope of the analysis

Operationally, the analysis drew primarily on a single ground handler and focused on the Wide-Body context. The Wide-Body focus was deliberate, as the most demanding and complex context yields requirements covering the broadest range of conditions; the reliance on one handler is a constraint, since each operates with its own equipment and routines, so the reality captured here reflects one way of working (KLM) rather than the full field.

In terms of stakeholders, the tension analysis was limited to the divergence between Schiphol and the ground handlers, the parties who provide the infrastructure and execute the connection. Other actors (airlines, technology developers, maintenance) shape the conditions too and bring tensions of their own, but fell outside this scope.

The concept is therefore grounded in its direct operational context, and transfer beyond it is not automatic: applicability to other handlers, to Narrow-Body operations, and to other airports, where the tensions, problems, and operating conditions differ, each requires its own validation first. Future work should integrate these perspectives and test in which operational context (Narrow-Body/Wide-Body) the autonomous concept makes the greatest impact.

Problem validation

The underlying problem has not yet been fully quantified. The research is motivated by docking issues in the inbound process, but the relative contribution of planning dynamics (the part an autonomous system primarily addresses) is still unknown. The data needed to determine it is currently being gathered by Schiphol. The concept has therefore been developed before the problem and business case are fully validated. This limitation is addressed directly in the roadmap: Horizon 0 focuses on quantifying the scale and relevance of planning dynamics.

Validation

The operational concept, roadmap, and requirements are an analytical synthesis, derived from interviews, observations, and co-creation. As such, they have not yet been validated against the operation itself: they were not reviewed with operations or Schiphol project developers, nor was their impact on planning dynamics tested through simulation.

A second assumption is technical. The concept takes for granted that what it describes is technically achievable, building on the Proof of Technology, but the underlying technical and orchestration assumptions (robot capabilities, the battery and charging strategy, and the integration with VDGS and ROS) have not themselves been tested or validated.

The roadmap is explicitly designed to close both gaps step by step: each horizon confirms these assumptions before the next is taken, and future work should use these steps both to test the concept and to keep refining the Adaptive North Star and roadmap as that experience grows.

Workshop composition and designer interpretation

The co-creation workshop included both Schiphol and ground handling perspectives, but the discussion leaned more strongly towards the ground handler side, so the operational perspective within Schiphol is represented less than the user perspective.

The Adaptive North Star and Horizon 3 concept are also more design interpretations than stakeholder-selected outcomes: they were synthesised by the researcher from the desired outcomes and tensions, so the result carries the researcher's framing of what the workshop input implied, chosen on the basis of the knowledge available at this stage.

Chapter 9 | Conclusion & Recommendations

9.1. Conclusion

The autonomous 400 Hz connection is integrated into Schiphol's inbound operation not as a finished design but as a clear yet adaptable direction, made concrete in the operational concept and reached through a learning-based development path.

The connection is not an isolated task. It is an interdependent step in an operation where activities depend on one another, and its value lies in the operational disadvantages automation can resolve: the connection is not always made on time, and the manual task is physically demanding (RQ1). Its limits are set by the fixed conditions, dependencies, and adoption risks it must work within (RQ2). Whether it succeeds depends on how well it integrates with the operation it enters.

That operation is not neutral ground: Schiphol and the ground handlers want different things from the system. Schiphol weighs it as an infrastructure provider, against scale, ownership, and its long-term airside ambition, while the handlers judge it by the daily reality at the stand, where it has to be present on time, stay controllable, and not slow the work down (RQ3). Where these strategic and operational interests pull apart, a design choice is needed rather than a condition the design can simply meet. Resolving these in co-design produced five shared choices: flexible deployment with a stability ambition, gradual autonomy with explicit role division, co-development as a condition for adoption, safe and workable behaviour, and building on existing digital infrastructure (RQ4).

These choices set the conditions but cannot fix the concept as a finished endpoint, because the future operation cannot be specified in advance. The direction is therefore held as an Adaptive North Star: a preferred future clear enough to commit to, yet explicit about what remains to be validated (RQ5). A Horizon 3 operational concept makes it concrete, and a horizon-based roadmap, reasoning backwards around learning milestones, sets out how to reach it.

The route from a technically proven connection to an operationally integrated one lies in a direction clear enough to commit to and open enough to adapt. By making the divergence between Schiphol and the ground handlers explicit and turning it into shared choices, the research gives Schiphol a grounded basis to take the first steps while keeping the route open as the operation, its people, and the technology evolve.

Recommendations

Validate the deployment model

The Horizon 3 concept assumes flexible deployment, the robot moving to where a handler cannot be present on time, but both Schiphol and the ground handlers were hesitant about a mobile solution, fearing new dependencies. Before investing further, Schiphol should validate whether there is operational support for this model, and whether predictive planning (positioning the robot proactively on expected inbound demand) can make it reduce the planning-dynamics problem rather than add another moving element.

Prioritise problem validation

The business case depends on how much of the docking problem stems from planning dynamics. Establishing this share, with a shared measurement standard for delayed connection, gives Schiphol an evidence-based basis for the investment decision (Horizon 0).

Choose where to start

Decide deliberately where to pilot first. A focused start, for example at the pier with the most docking issues, builds evidence in the highest-impact context; it also warrants reconsidering whether Wide-Body remains the right entry point or whether Narrow-Body offers a simpler, higher-volume case.

Continue co-developing with ground handlers

Continue the collaborative way of working established in this project. In the co-creation, participants noted that decisions are typically made at a strategic level without operational input, and that they would value far more consultation between Schiphol and the handlers. The recommendation is therefore not only to involve handlers in this concept, but to find out how to structure cross-level collaboration as a standing way of working. Especially because the co-creation session showed how naturally they engage with these questions and how valuable their input is. One possible way to start is embedding an operational representative in the development team from the start, as set out in Horizon 0.

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Appendix

AI use and reflection

During this research, artificial intelligence (AI) tools, specifically ChatGPT, Copilot, Claude, and Vizcom were used to support the writing and research process. This section reflects on how they were used, where they genuinely helped, and where I noticed they did not.

AI was used for several things: language and writing support, thinking through the structure of the report, sparring on and reflecting critically on my ideas, and translating my own sketches into the concept visualisations (the current workflow and the Horizon 3 operational workflow). Within Schiphol, Copilot was used in a secure company environment to search and review internal documents.

Role of AI in the process

Looking back, AI helped most with writing. I wrote the chapters myself, but using it to tighten my text, improve the English, and make passages shorter and more to the point made a difference to the readability of the final report. I also used it as a sparring partner and a critical reflector on my work, testing whether my reasoning held up and where it could be sharpened.

It was useful in the ideation phase too, though here with a clear condition: when I sparred on initial ideas I already had, it helped me develop them further, but without my own input as a starting point it was not particularly creative on its own.

Finally, it was genuinely useful for visualisation: I created the sketches and ideas myself, and the tools helped turn them into concept images that communicate the concept within its context more clearly than my sketches alone could.

Limitations

I also noticed the limits. When I used AI to think through how to structure the report, it could suggest orderings, but it struggled to distinguish main points from side issues, treating everything I gave it as equally important. The decisions about emphasis I had to make myself.

The visualisations came with a limitation too. The sketches were mine, but the AI added its own interpretation when generating the images, introducing elements I had not intended. This is a form of bias, which is also why the visuals are presented as directional impressions rather than precise designs.

Across all of this, AI was a supporting tool that sped up writing, structuring, and visualisation, but the research, the judgement, and the design decisions remained my own.

Appendix A - developments at other airports

The autonomous 400 Hz connection is one element of a broader international movement towards automation at airports. The examples below illustrate that the operational integration of autonomous systems into the airport environment is an active challenge worldwide. They are drawn from publicly available news reporting and are included for illustration only; the sources are listed inline rather than in the main reference list.

- Changi Airport (Singapore) — fully driverless baggage tractors operating between terminals and aircraft stands, monitored from a control centre with remote operators and running alongside human-driven vehicles in marked autonomous-vehicle zones. aerospaceglobalnews.com

- Kansai International Airport (Japan) — trials of Level 4 autonomous baggage tow tractors on the ramp using EasyMile technology. futuretransport-news.com

- Munich Airport (Germany) — automation of cargo handling as a benchmark for airside logistics. munich-airport.com

- New York area airport (United States): testing of self-driving passenger shuttles. nypost.com

- Japanese airports — trials of humanoid robots to support physically demanding baggage-handling tasks. theguardian.com

- Bengaluru Airport (India) — use of artificial intelligence at key runway zones to improve airside safety. timesofindia.indiatimes.com

- Airport ground handling (general) — an overview of how robotics and automation are increasingly applied to enhance airport ground-handling operations. aerotime.aero

Appendix B: Proof of Technology

This appendix describes the Proof of Technology that forms the technical starting point for this research. In November 2025, Schiphol demonstrated ARC (Autonomous Robot for GPU Connection), a robotic system able to perform the physical 400 Hz connection autonomously. Its capabilities are summarised here at a high level as background to the operational concept developed in the main report. The description draws on the demonstration and documentation [55].

Robot components

The robot consists of three main parts: a mobile platform that moves it around the apron and carries the load, a robotic arm that performs the precise interaction with the aircraft, and a software layer that handles high-level behaviour and coordinates navigation, vision, manipulation, safety, and diagnostics.

Navigation

The robot navigates autonomously, combining predefined routes with dynamic path planning. It follows fixed routes along the apron's markings, and because the apron is a dynamic environment, it continuously detects obstacles such as vehicles, equipment, and people. When an obstacle appears, it temporarily deviates from its route and returns once the path is clear.

Connection

After reaching the stand position, the arm performs the connection in two main steps: it detects and opens the access panel autonomously, and then locates the socket and inserts the 400 Hz connector with controlled force. Reliable socket detection is one of the more challenging aspects, as the socket is often shadowed, occluded, or affected by reflections.

Cable handling

The mobile platform tows the 400 Hz cable from the ground power unit to the aircraft, so the arm is used only for the static connection task rather than for carrying the cable. Because the platform relies on laser scanners for obstacle detection, the cable is kept clear of the scanners' detection zones to avoid being registered as an obstacle, which constrains how the robot approaches and manoeuvres.

Safety

The system uses layered, laser-based safety zones with dynamic speed limiting for safe operation in mixed human–robot environments. Moving inward, the zones reduce the robot's speed, bring it to a stop, and ultimately trigger an emergency stop. This graded approach enables responsive safety behaviour rather than a binary stop-or-go operation.

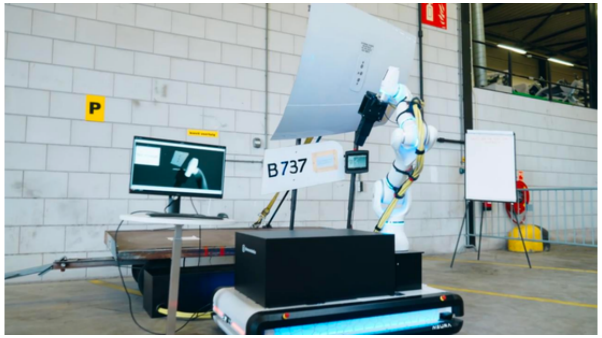


Figure B.1: Proof of Technology: demonstration of ARC (Autonomous Robot for Connection)

Appendix C - Stakeholder analysis

A stakeholder analysis was conducted to map the parties involved in and affected by the autonomous 400 Hz connection, and to clarify their roles, responsibilities and interdependencies within Schiphol's airside operations. A distinction is made between direct and indirect stakeholders, as this clarifies which parties are directly involved in or affected by the daily operation of the autonomous system, and which shape the broader conditions within which it must function. Direct stakeholders include Schiphol as the infrastructure provider, ground handling companies as current executors of the connection, airlines as dependent on reliable aircraft handling, and maintenance and infrastructure services as responsible for stand system availability. Indirect stakeholders, such as governance actors, passengers, other airports, and technology developers, influence regulation, service quality, and technical development.

DIRECT STAKEHOLDERS

SCHIPHOL

Role: provides stand infrastructure and related equipment for ground handling operations, and shapes the orchestration context for future autonomous airside operations

Interest: operational efficiency, reduced emissions, capacity, future readiness

GROUND HANDLERS

Role: perform the turnaround process at the stand, using the infrastructure provided by Schiphol

Interest: workable and safe operations, reduced physical strain, lower dependency on staff availability, low last minute changes/interruptions

AIRLINES

Role: operate the aircraft and are responsible for transporting passengers safely and efficiently while maintaining service quality

Interest: timely and reliable aircraft handling at the stand in order to support efficient turnaround operations

MAINTENANCE & INFRA

Role: inspect, maintain, and repair the GSE and related stand infrastructure

Interest: reliable equipment performance, maintainability of current and future infrastructure

INDIRECT STAKEHOLDERS

GOVERNANCE

Role: defines the regulatory & safety conditions within which autonomous airside operations must be developed and implemented

Interest: risk reduction and accountability

PASSENGERS

Role: satisfaction is affected by the efficiency and reliability of turnaround operations

Interest: fewer delays, smoother operations, and improved travel experience

OTHER AIRPORTS

Role: represent a broader context for future transferability and scaling of the concept

Interest: learning from successful implementation, applicability in other airport contexts and transferable automation strategies

TECH DEVELOPERS

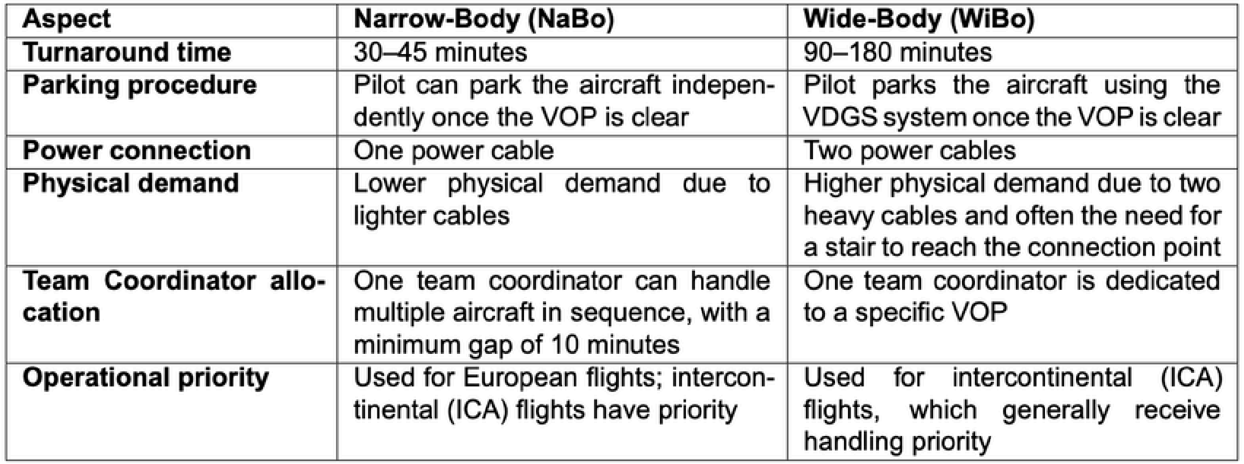
Role: design and develop the autonomous connection system

Interest: technical feasibility, robust system performance, successful integration into operations, scalability of the solution

Figure C.1: Direct and indirect stakeholders of the autonomous 400 Hz connection, with their roles and primary interests

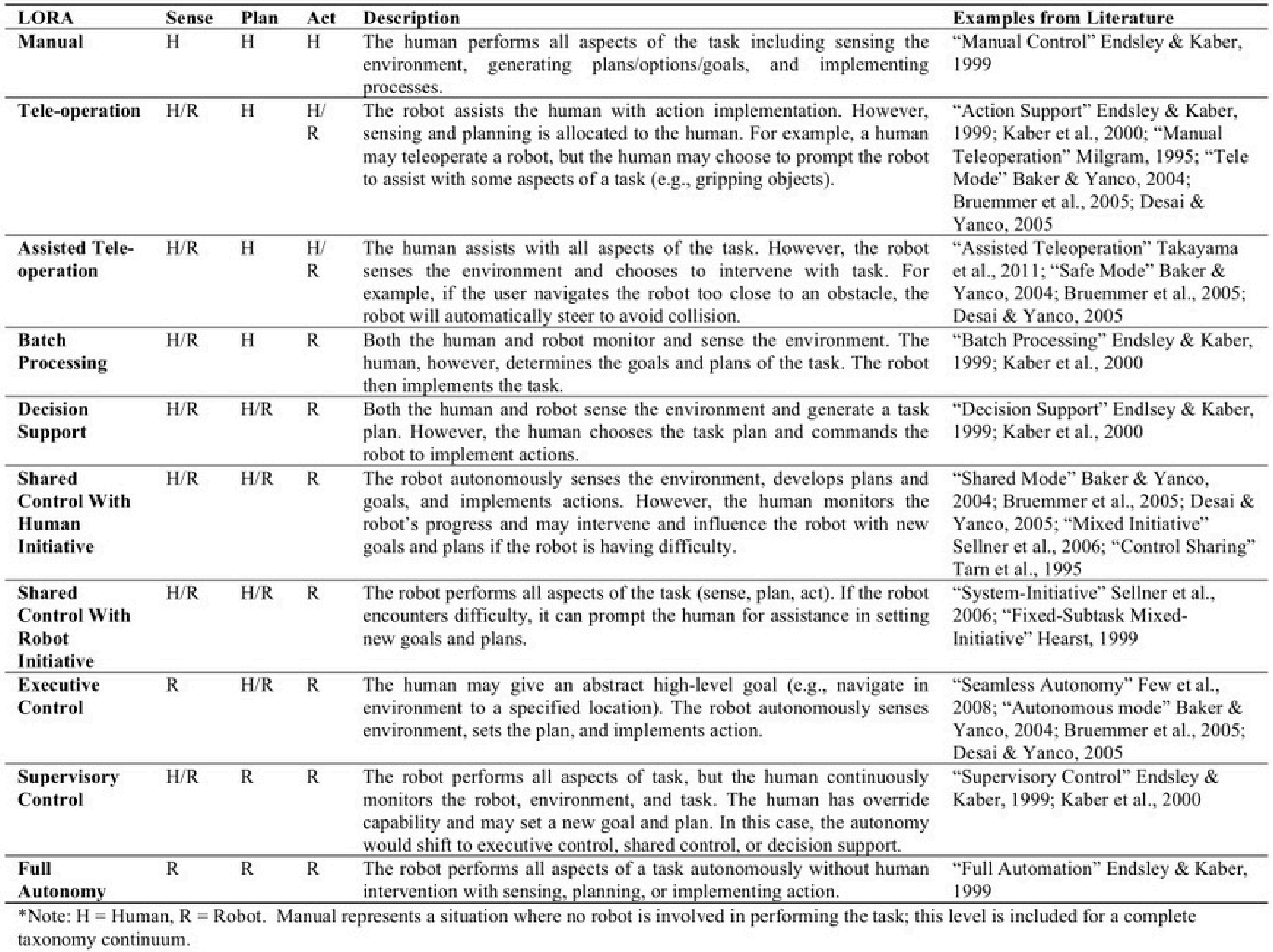
Appendix D - Narrow-Body and Wide-Body comparison

Table D.1: Comparison of Narrow-Body and Wide-Body operational contexts across key dimensions relevant to the autonomous 400 Hz connection



Aspect	**Narrow-Body (NaBo)**	**Wide-Body (WiBo)**
Turnaround time	30–45 minutes	90–180 minutes
Parking procedure	Pilot can park the aircraft independently once the VOP is clear	Pilot parks the aircraft using the VDGS system once the VOP is clear
Power connection	One power cable	Two power cables
Physical demand	Lower physical demand due to lighter cables	Higher physical demand due to two heavy cables and often the need for a stair to reach the connection point
Team Coordinator allocation	One team coordinator can handle multiple aircraft in sequence, with a minimum gap of 10 minutes	One team coordinator is dedicated to a specific VOP
Operational priority	Used for European flights; intercontinental (ICA) flights have priority	Used for intercontinental (ICA) flights, which generally receive handling priority

Appendix E: Levels of Robot Automation



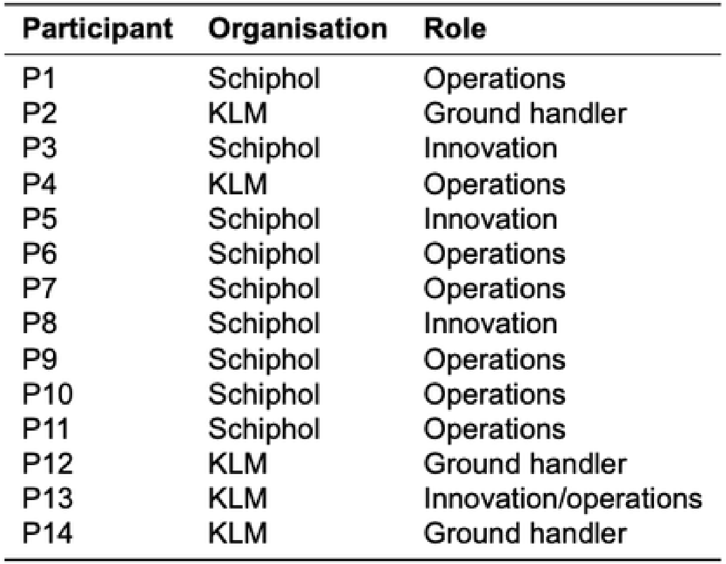
LORA	Sense	Plan	Act	Description	Examples from Literature
Manual	H	H	H	The human performs all aspects of the task including sensing the environment, generating plans/options/goals, and implementing processes.	"Manual Control" Endsley & Kaber, 1999
Tele-operation	H/R	H	H/R	The robot assists the human with action implementation. However, sensing and planning is allocated to the human. For example, a human may teleoperate a robot, but the human may choose to prompt the robot to assist with some aspects of a task (e.g., gripping objects).	"Action Support" Endsley & Kaber, 1999; Kaber et al., 2000; "Manual Teleoperation" Milgram, 1995; "Tele Mode" Baker & Yanco, 2004; Bruemmer et al., 2005; Desai & Yanco, 2005
Assisted Tele-operation	H/R	H	H/R	The human assists with all aspects of the task. However, the robot senses the environment and chooses to intervene with task. For example, if the user navigates the robot too close to an obstacle, the robot will automatically steer to avoid collision.	"Assisted Teleoperation" Takayama et al., 2011; "Safe Mode" Baker & Yanco, 2004; Bruemmer et al., 2005; Desai & Yanco, 2005
Batch Processing	H/R	H	R	Both the human and robot monitor and sense the environment. The human, however, determines the goals and plans of the task. The robot then implements the task.	"Batch Processing" Endsley & Kaber, 1999; Kaber et al., 2000
Decision Support	H/R	H/R	R	Both the human and robot sense the environment and generate a task plan. However, the human chooses the task plan and commands the robot to implement actions.	"Decision Support" Endlsey & Kaber, 1999; Kaber et al., 2000
Shared Control With Human Initiative	H/R	H/R	R	The robot autonomously senses the environment, develops plans and goals, and implements actions. However, the human monitors the robot's progress and may intervene and influence the robot with new goals and plans if the robot is having difficulty.	"Shared Mode" Baker & Yanco, 2004; Bruemmer et al., 2005; Desai & Yanco, 2005; "Mixed Initiative" Sellner et al., 2006; "Control Sharing" Tarn et al., 1995
Shared Control With Robot Initiative	H/R	H/R	R	The robot performs all aspects of the task (sense, plan, act). If the robot encounters difficulty, it can prompt the human for assistance in setting new goals and plans.	"System-Initiative" Sellner et al., 2006; "Fixed-Subtask Mixed-Initiative" Hearst, 1999
Executive Control	R	H/R	R	The human may give an abstract high-level goal (e.g., navigate in environment to a specified location). The robot autonomously senses environment, sets the plan, and implements action.	"Seamless Autonomy" Few et al., 2008; "Autonomous mode" Baker & Yanco, 2004; Bruemmer et al., 2005; Desai & Yanco, 2005
Supervisory Control	H/R	R	R	The robot performs all aspects of task, but the human continuously monitors the robot, environment, and task. The human has override capability and may set a new goal and plan. In this case, the autonomy would shift to executive control, shared control, or decision support.	"Supervisory Control" Endsley & Kaber, 1999; Kaber et al., 2000
Full Autonomy	R	R	R	The robot performs all aspects of a task autonomously without human intervention with sensing, planning, or implementing action.	"Full Automation" Endsley & Kaber, 1999

*Note: H = Human, R = Robot. Manual represents a situation where no robot is involved in performing the task; this level is included for a complete taxonomy continuum.

Figure E.1: Levels of Robot Autonomy (LORA) taxonomy, allocating responsibility for sensing, planning, and acting between human and robot across ten levels, ranging from full manual control to full autonomy [15].

Appendix F: Interview participants

Table F.1: Overview of interview participants and their roles



Participant	Organisation	Role
P1	Schiphol	Operations
P2	KLM	Ground handler
P3	Schiphol	Innovation
P4	KLM	Operations
P5	Schiphol	Innovation
P6	Schiphol	Operations
P7	Schiphol	Operations
P8	Schiphol	Innovation
P9	Schiphol	Operations
P10	Schiphol	Operations
P11	Schiphol	Operations
P12	KLM	Ground handler
P13	KLM	Innovation/operations
P14	KLM	Ground handler

Interview topics

The interviews were conducted as semi-structured conversations. The exact questions were adapted to each participant's role, but generally covered the following topics:

- The participant's role and involvement in inbound airside operations or the 400 Hz connection process.
- The current 400 Hz connection process, including responsibilities, timing, dependencies, and practical deviations from the formal procedure.
- Operational bottlenecks, such as staff availability, planning changes, equipment placement, physical handling, stand layout, and timing of the connection.
- Interactions with related stand processes, including VDGS, passenger boarding bridges, PCA, chocks, cones, catering, baggage, and other ground equipment.
- The possible value of automation, including reliability, safety, reduced physical workload, staff dependency, and operational availability.
- Conditions for implementation, such as ownership, maintenance, supervision, stakeholder acceptance, certification, business case, and fit with Schiphol's long-term autonomous airside vision.

Appendix G: Prioritising considerations

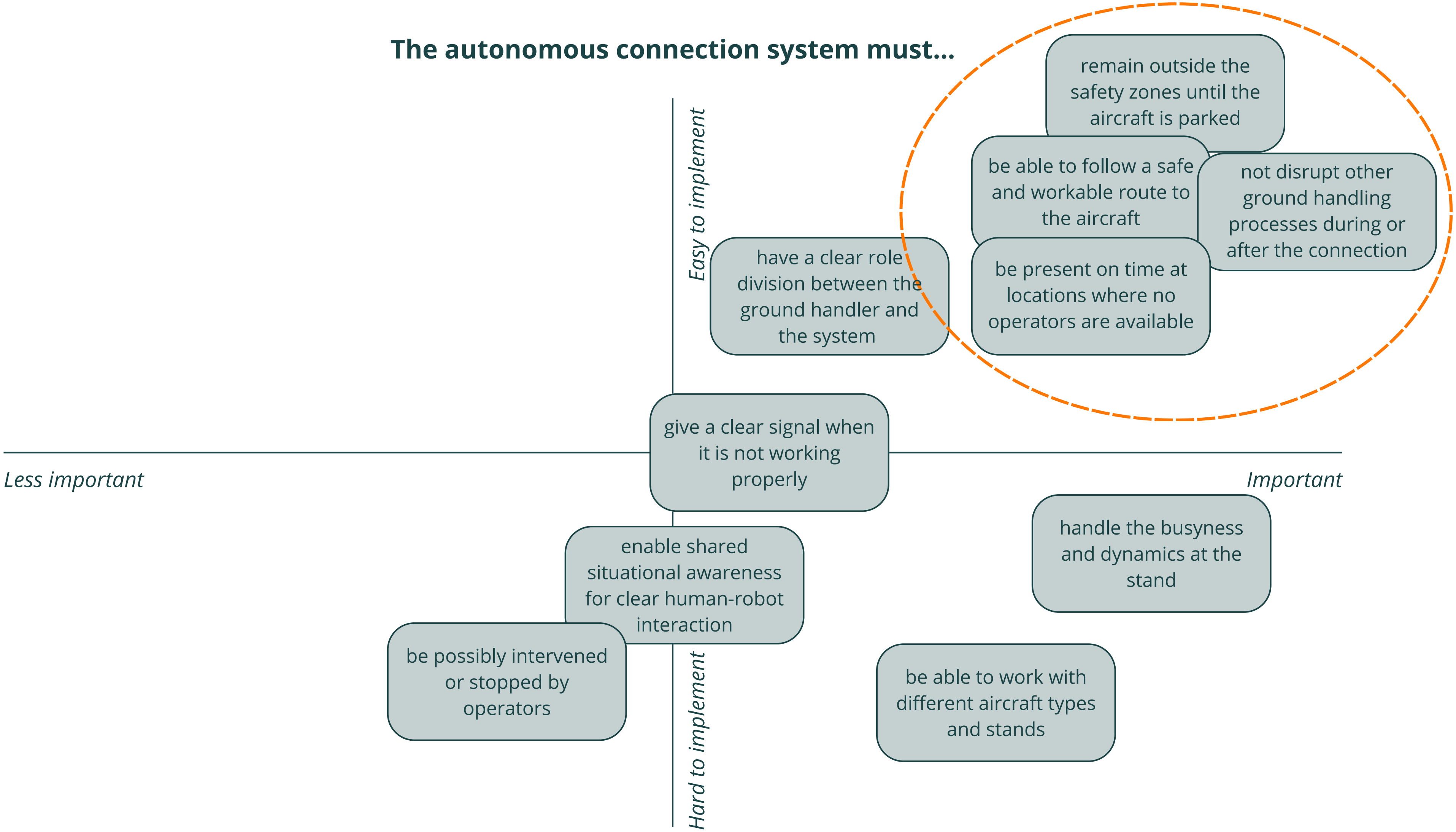


Figure G.1: Prioritisation of design considerations for the autonomous 400 Hz connection system according to importance and ease of implementation (IE-matrix). The orange circle highlights the considerations that form the main operational design focus.

Appendix H: Speculative positioning scenarios

This appendix documents a speculative scenario evaluation carried out as an additional, exploratory activity early in the research. Three positioning scenarios were evaluated with innovation practitioners to probe how fundamentally different deployment options might be received. The activity is not part of the core line of reasoning, but it surfaced two concerns, adoption and human-robot role division, that recur throughout the project and supported the decision to take these as central conditions rather than treating positioning alone as the design problem. This appendix provides the full method, scenarios, and findings.

Method

Following Dunne and Raby [26], the scenarios were used not to predict the future but to open discussion about possible futures and to surface the conditions under which different directions become desirable or problematic. Where the interviews focused on the current operation, the scenario evaluation confronted participants with future situations that do not yet exist, surfacing concerns and consequences that direct questions about the present cannot reveal. Each scenario was evaluated using an unexpected-consequences method: participants first identified potential value and concerns, after which three iterative rounds were completed, each surprising consequence becoming the starting point for the next. Figure [H.2] shows the template used.

The evaluation was conducted in a co-creation session with eight innovation practitioners from Schiphol, purposively selected for their experience with airside innovation. This early, exploratory step aimed to understand how a range of fundamentally different positioning options would be received, for which a broad innovation and strategy perspective was most suitable. The deeper involvement of ground handlers in shaping the desired future takes place in the co-design process in Chapter 6, where their operational perspective is central.

The three scenarios were developed by the researcher and therefore reflect particular framings. To limit the influence of this framing, they were deliberately chosen to span three distinct configurations (reactive, shared, and structural), and the unexpected-consequences method was used to surface participants' own associations rather than steer them.

Scenario descriptions

The scenarios were developed through an iterative sketching process exploring different physical and operational positions of the system in relation to the aircraft, the FPU infrastructure, and the surrounding stand process. Three distinct positioning logics emerged, translated into the descriptions below: the Stand-In Robot, the Zone Robot, and the Autonomous Gate. (Figure [H.1])

- Scenario 1 — The Stand-In Robot (reactive). It is 9:00 during the summer peak, and the schedule is tight. An arriving aircraft lands early while a departing one is delayed, creating a gap. Five minutes before arrival, the system detects that no staff is present at the assigned stand and the responsible crew is still occupied elsewhere. The robot moves to the stand and, once the aircraft is blocked, connects the 400 Hz power so the engines can shut down. Flexibly deployable; responds to planning disruptions; corrects unexpected disturbances.

- Scenario 2 — The Zone Robot (shared). A busy afternoon with multiple arrivals in a short window. Intercontinental flights take priority, affecting smaller aircraft with short turnarounds. To stabilise this, Schiphol has assigned one connection robot to a zone of five to six adjacent stands. Within this zone the robot is part of the standard arrival operation and is planned in to support incoming flights, deployed at the last moment when no staff is available. Stabilises peak load; deployed within a defined zone; shared capacity.

- Scenario 3 — The Autonomous Gate (structural). Because of persistent staff shortages, Schiphol has adapted its infrastructure to run the arrival process autonomously up to engine shutdown. Twenty gates can now do this, including F18, where no staff is scheduled for this phase. The aircraft is docked by the system and the 400 Hz cable is connected; once passengers have disembarked, ground crew take over the rest of the turnaround. Robustly integrated into the infrastructure; reliable; a structural part of the arrival process.

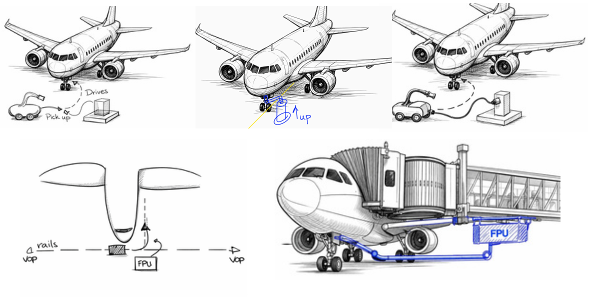


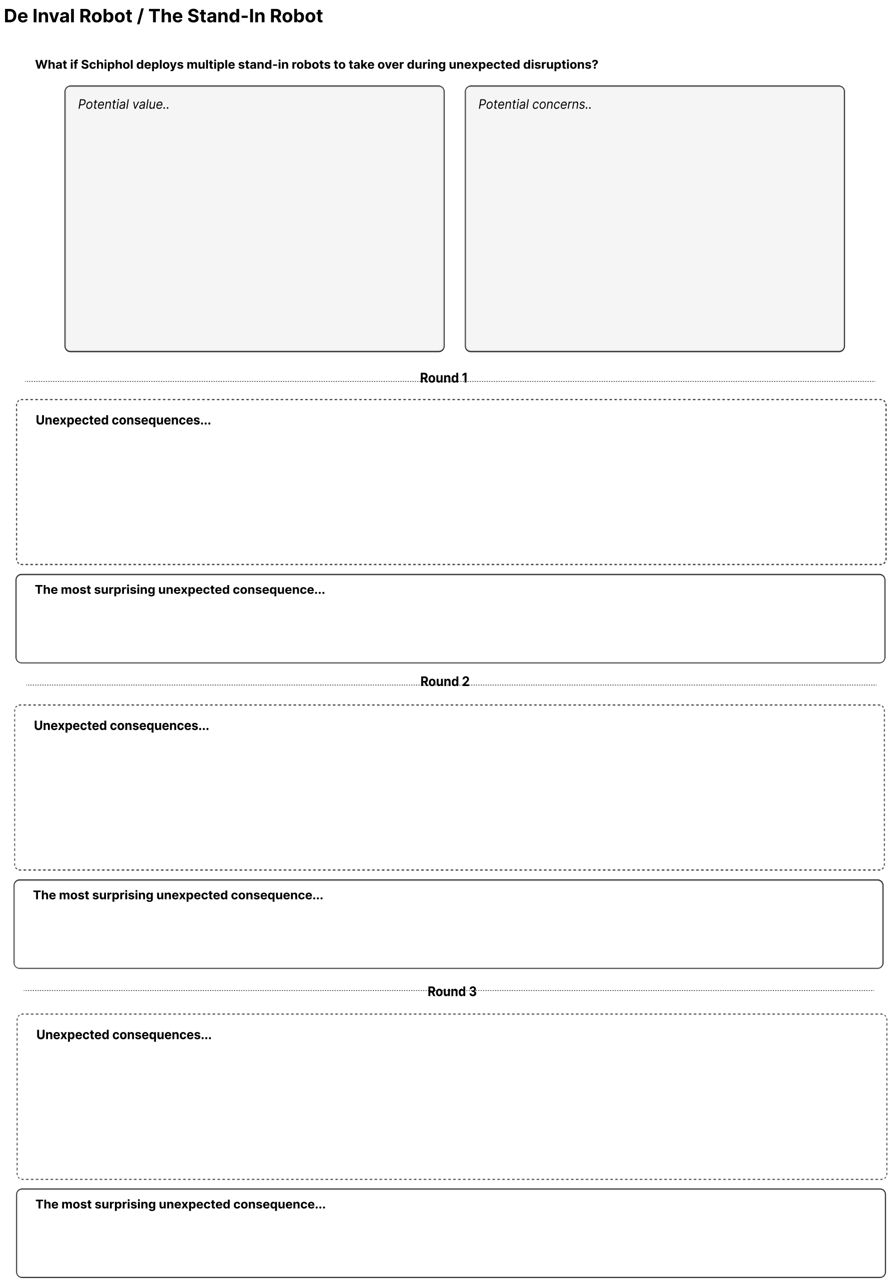
Figure H.1: Iterative sketches used to explore the physical and operational positioning of the autonomous 400 Hz connection system. The sketches were initially developed by the researcher and refined using ChatGPT. From this exploration, three scenario logics emerged: flexible deployment, zone-based deployment and structural gate integration.

Evaluation findings
The evaluation generated insights that cut across all three scenarios rather than scenario-specific conclusions. The dominant theme was the human-robot relationship: across every scenario, participants responded primarily to how responsibility would be divided between the ground handler and the system, and whether it would be trusted and used in practice, rather than to the differences in positioning. This points to adoption and a clear human-robot role division as central conditions. Further themes concerned the trade-off between back-up and structural deployment, investment justification, the conditions under which physical strain is actually eliminated, and reliability. The full results per scenario follow.

Scenario 1 — The Stand-In Robot
- Potential value: prevents domino effects from planning disruptions; supports ground handlers at peak moments; reduces emissions from waiting aircraft.
- Concerns: uncertain reliability (incorrect detection or failure); hard to plan how far in advance the need can be identified; risks disrupting planning rather than solving it; reduced motivation for handlers to be present on time.
- Unexpected consequence: poor adoption management leads to manipulation of the robot and eventually to termination of robot projects; as automation is rolled back, staff are needed again, but qualified personnel are no longer available.

Scenario 2 — The Zone Robot
- Potential value: deployable when no staff is available; supports the process without replacing handlers; flexible with planning variability.
- Concerns: high investment for limited, unpredictable use; physical strain remains when the robot is not deployed.
- Unexpected consequence: handlers become disengaged and stop paying attention; additional protocols are needed to manage the interaction, making the operation more complex rather than simpler.

Scenario 3 — The Autonomous Gate
- Potential value: cost-efficient through continuous, structural use; not dependent on staff availability; keeps personnel out of the emission zone; reduces preventable emissions through timely connection.
- Concerns: high upfront investment; limited flexibility; technology-dependent, as all circumstances must be handled autonomously; high energy consumption.
- Unexpected consequence: poor adoption leads to vandalism and active resistance, with a man-versus-machine dynamic that could escalate into strikes and organised opposition; the airport risks splitting into an autonomous and a manual part, creating two operational cultures.



De Inval Robot / The Stand-In Robot

What if Schiphol deploys multiple stand-in robots to take over during unexpected disruptions?

Potential value..

Potential concerns..

Round 1

Unexpected consequences...

The most surprising unexpected consequence...

Round 2

Unexpected consequences...

The most surprising unexpected consequence...

Round 3

Unexpected consequences...

The most surprising unexpected consequence...

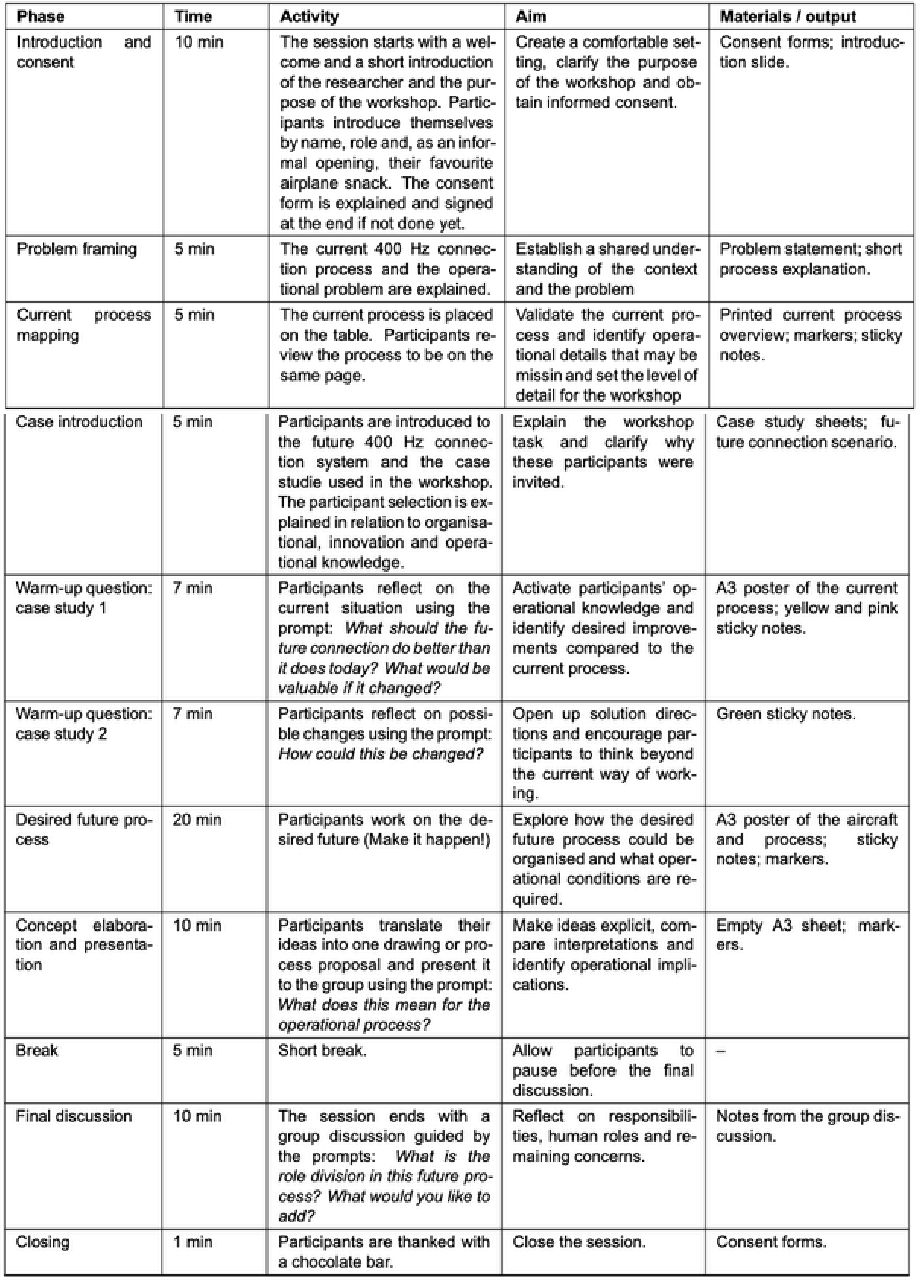
Figure H.2: The unexpected-consequences template used in the scenario evaluation. Participants first noted the potential value and concerns of the scenario, after which three iterative rounds were completed; in each round, the most surprising consequence became the starting point for the next.

Appendix I: Co-creation session to make design decisions between tensions

This appendix presents the full protocol of the co-creation workshop introduced in Chapter 6, in which the five tensions were turned into design choices with Schiphol and ground handling participants. It sets out the protocol, the materials, outputs of the workshop.

The protocol

Table I.1: Protocol for the co-creation workshop



Phase	Time	Activity	Aim	Materials / output
Introduction and consent	10 min	The session starts with a welcome and a short introduction of the researcher and the purpose of the workshop. Participants introduce themselves by name, role and, as an informal opening, their favourite airplane snack. The consent form is explained and signed at the end if not done yet.	Create a comfortable setting, clarify the purpose of the workshop and obtain informed consent.	Consent forms; introduction slide.
Problem framing	5 min	The current 400 Hz connection process and the operational problem are explained.	Establish a shared understanding of the context and the problem	Problem statement; short process explanation.
Current process mapping	5 min	The current process is placed on the table. Participants review the process to be on the same page.	Validate the current process and identify operational details that may be missin and set the level of detail for the workshop	Printed current process overview; markers; sticky notes.
Case introduction	5 min	Participants are introduced to the future 400 Hz connection system and the case studie used in the workshop. The participant selection is explained in relation to organisational, innovation and operational knowledge.	Explain the workshop task and clarify why these participants were invited.	Case study sheets; future connection scenario.
Warm-up question: case study 1	7 min	Participants reflect on the current situation using the prompt: *What should the future connection do better than it does today? What would be valuable if it changed?*	Activate participants' operational knowledge and identify desired improvements compared to the current process.	A3 poster of the current process; yellow and pink sticky notes.
Warm-up question: case study 2	7 min	Participants reflect on possible changes using the prompt: *How could this be changed?*	Open up solution directions and encourage participants to think beyond the current way of working.	Green sticky notes.
Desired future process	20 min	Participants work on the desired future (Make it happen!)	Explore how the desired future process could be organised and what operational conditions are required.	A3 poster of the aircraft and process; sticky notes; markers.
Concept elaboration and presentation	10 min	Participants translate their ideas into one drawing or process proposal and present it to the group using the prompt: *What does this mean for the operational process?*	Make ideas explicit, compare interpretations and identify operational implications.	Empty A3 sheet; markers.
Break	5 min	Short break.	Allow participants to pause before the final discussion.	–
Final discussion	10 min	The session ends with a group discussion guided by the prompts: *What is the role division in this future process? What would you like to add?*	Reflect on responsibilities, human roles and remaining concerns.	Notes from the group discussion.
Closing	1 min	Participants are thanked with a chocolate bar.	Close the session.	Consent forms.

The materials

- TC en TMs rijden naar de VOP
- FPU's staan op het FPU eiland

- FPU wordt aangesloten als:
    - de anti-collision lights uit zijn
    - De voorwielen zijn geblokt

- Trap wordt naar het vliegtuig gereden
- FPU kabels worden uitgerold en naar het vliegtuig getrokken

- Panel wordt geopend
- Kabel wordt ingeplugd
- Stroom wordt aangezet op de plug
- De kabel wordt gezekerd

- FPU licht wordt groen zodra stroom is aangesloten
- Piloot schakelt de motoren uit

Figure I.1: Current 400 Hz connection workflow used as input for the co-creation workshop. The visual was used to create a shared understanding of the existing process and to allow participants to formulate problems. Image generated with the assistance of ChatGPT.

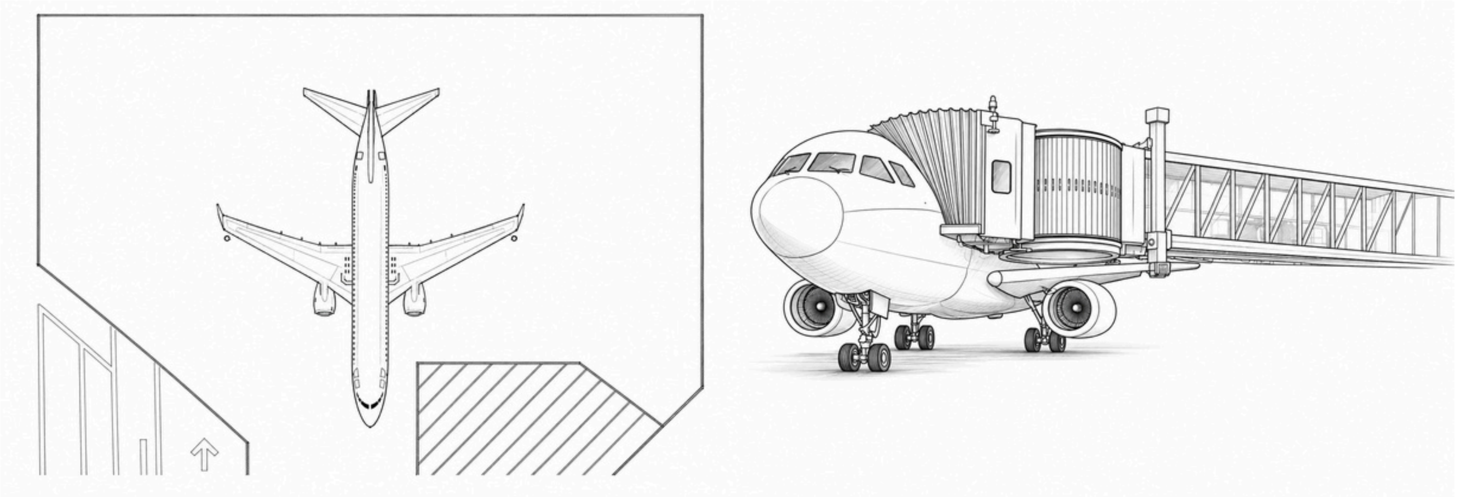
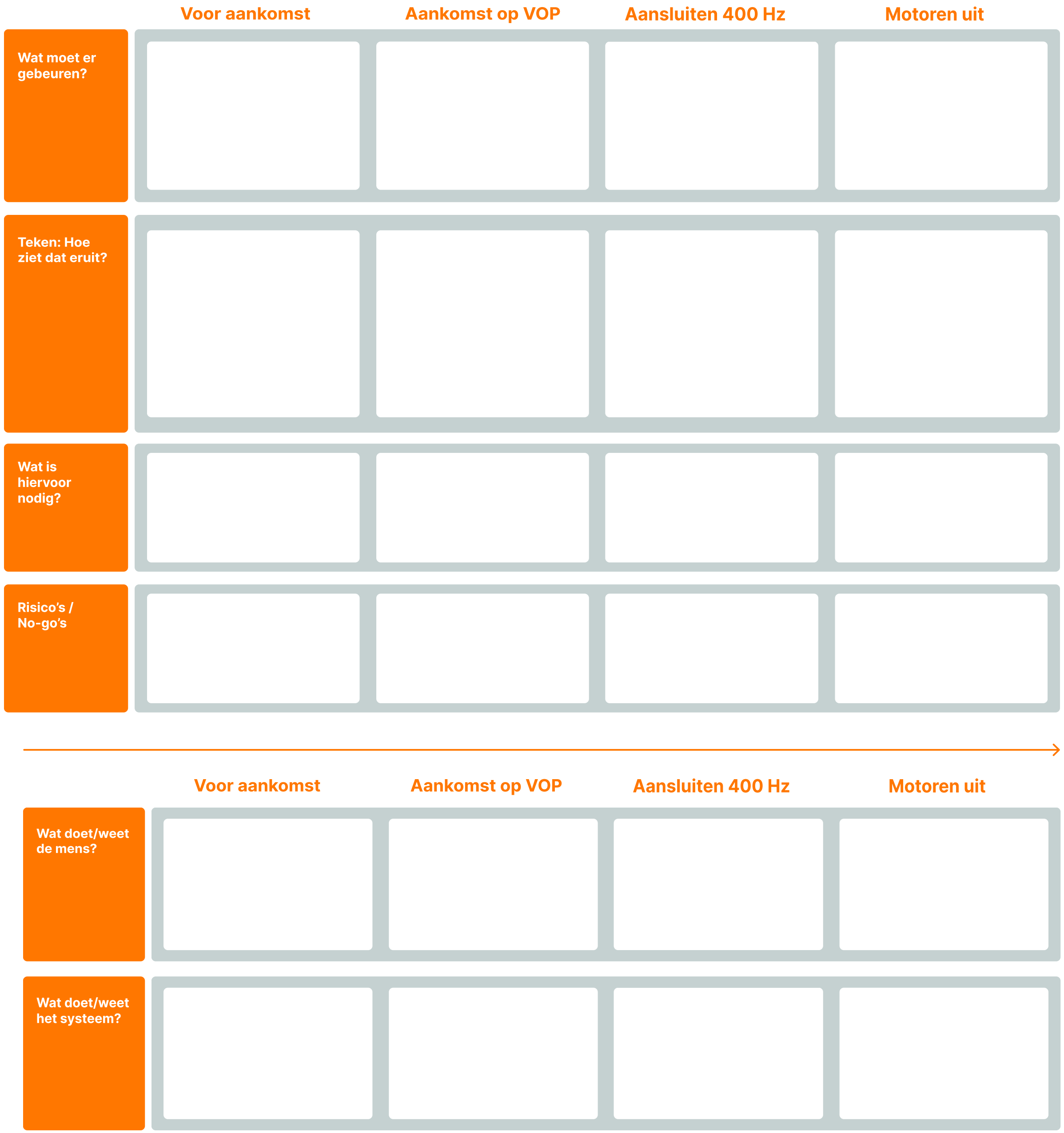


Figure I.2: Visual templates used during the co-creation workshop. The side-view and top-view drawings supported participants in sketching how an autonomous 400 Hz connection system could be positioned around the aircraft and integrated into the stand environment. Image generated with the assistance of ChatGPT.

The materials



	Voor aankomst	Aankomst op VOP	Aansluiten 400 Hz	Motoren uit
Wat moet er gebeuren?				
Teken: Hoe ziet dat eruit?				
Wat is hiervoor nodig?				
Risico's / No-go's				

	Voor aankomst	Aankomst op VOP	Aansluiten 400 Hz	Motoren uit
Wat doet/weet de mens?				
Wat doet/weet het systeem?				

Figure I.3: Co-creation template used to structure participants' ideas for the desired future workflow

The outputs

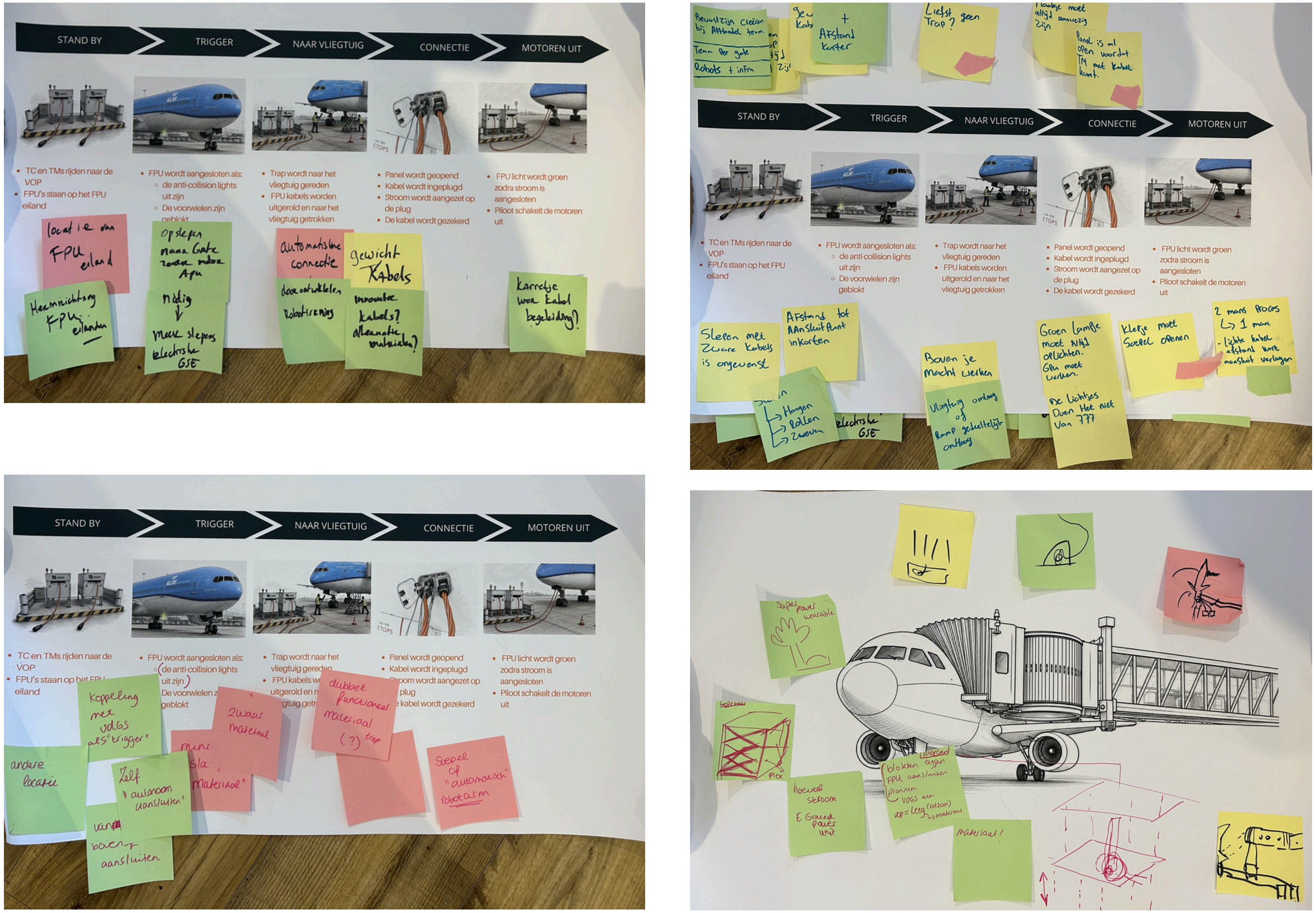
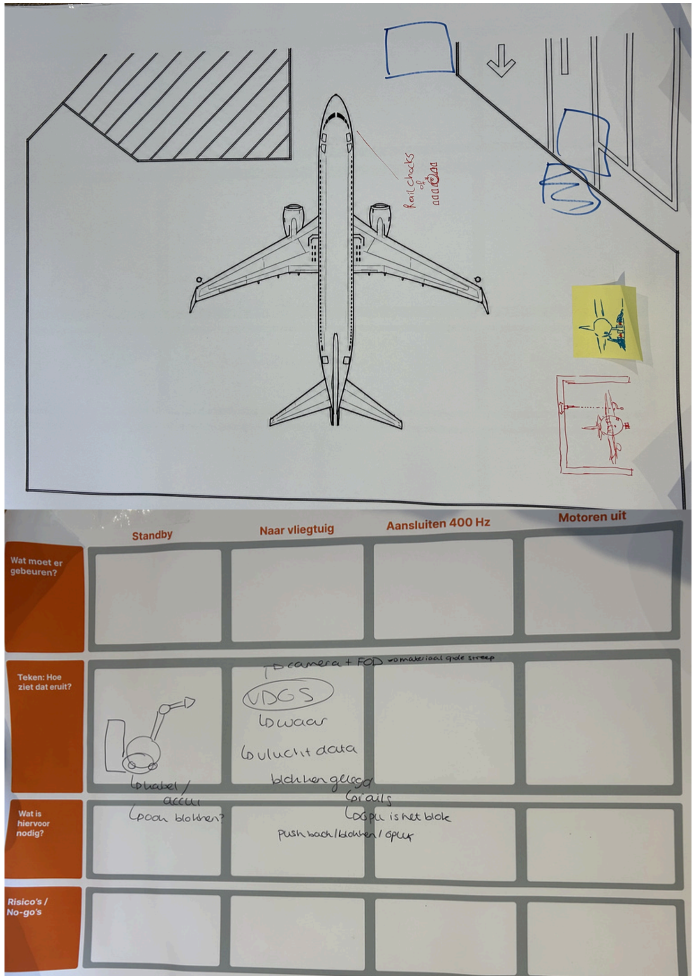


Figure I.4: Output Q4/Q5/Q6

The outputs



	Standby	Naar vliegtuig	Aansluiten 400 Hz	Motoren uit
Wat moet er gebeuren?				
Teken: Hoe ziet dat eruit?	↳kabel / accu	→camera + FOD →materiaal gele streep VDGS ↳waar ↳vlucht data blokken gelegd		
Wat is hiervoor nodig?	↳door blokken?	↳rails ↳GPU is het blok push back/blokken/GPU		
Risico's / No-go's				

Figure I.5: Output Q6

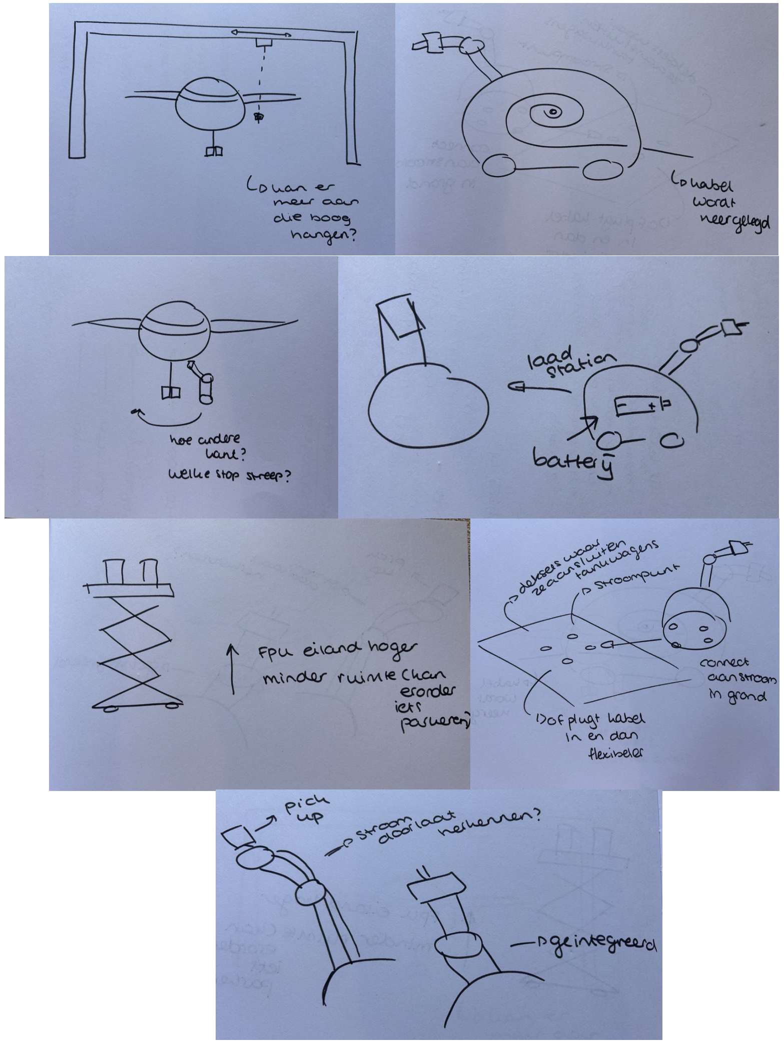


Figure I.6: Overview of the connection concepts generated during the co-creation workshop, redrawn from participants' sketches and discussion.

Appendix J: Tension decision - full reasoning

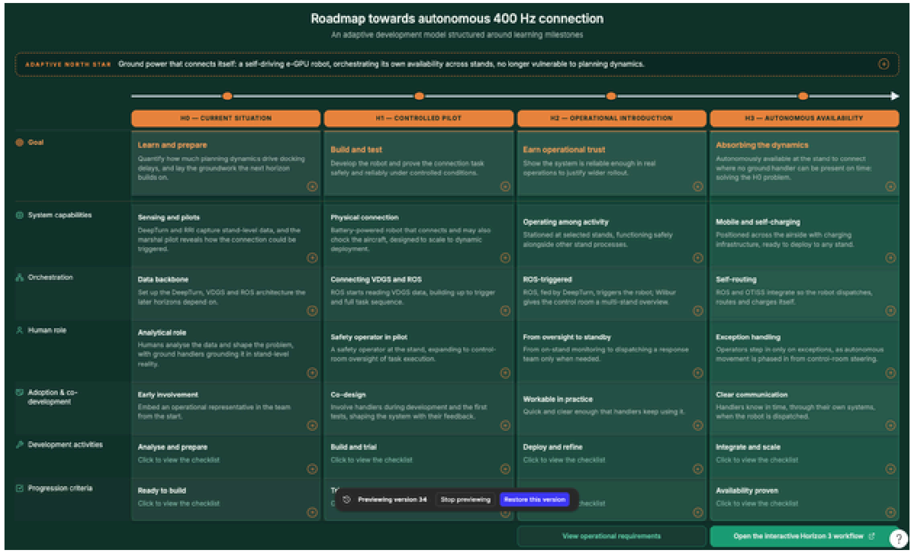
Table J.1: Tensions within autonomous connection, identifying where the requirements of Schiphol and ground handlers diverge and where design decisions must be made (extended version)

#	Tension decision	Explanation
T1:	**Flexible deployment with stability ambition**	Participants consistently expressed a preference for stand-level availability: a system that is present when needed without requiring dispatch or coordination. ``*It should be like the PCA unit, it could move ten metres, but not shift a hundred metres to the next stand*'' (WP3). A mobile or zone-based system was seen as adding complexity to an already dynamic operation. At the same time, structural on-gate deployment at every stand is not immediately feasible: the investment required is significant and difficult to justify without a proven business case. This tension is not resolved by choosing one option over the other. The starting point is a flexible deployment model, but one that must be explicitly designed to bring stability rather than add complexity. Any deployment choice must therefore be evaluated on whether it structurally reduces the vulnerability of the connection process to planning dynamics, rather than shifting the same problem from a ground handler who may not be present to a robot that may not be positioned in time. If needed and as operational experience grows and the business case develops, more structural forms of on-gate integration can be explored in later development phases.
T2:	**Gradual autonomy with explicit role division**	Participants recognised a transition phase in which humans and robots coexist at the stand. During this phase, they preferred the ability to initiate the robot manually: ``*you manually activate it, so there is still a form of control*'' (WP3). At the same time, the long-term ambition was clear: ``*in fifteen years, I hope there is nobody on the platform during the arrival process because the air quality is bad*'' (WP4). Since the robot's primary purpose is to be present when no ground handler is available on time, autonomy is the operational goal. However, during the transition phase when humans and robot may still coexist at the stand, each development step must explicitly define the role of both: what the robot does independently, what the ground handler monitors or confirms, and how the robot communicates its actions so that ground handlers can understand and anticipate its behaviour. As long as people are still present at the stand, the robot must remain physically predictable and its actions interpretable, so that working alongside it feels safe and controllable rather than unpredictable. Even as the system moves towards higher levels of autonomy some form of human oversight remains relevant and can be gradually reduced as operational trust and system reliability grow.
T3:	**Co-development as a condition for adoption**	The closing discussion surfaced a broader concern about the relationship between Schiphol and ground handling parties. Participants noted that decisions are typically made at a strategic level without operational input: ``*I never know where to go*'' (WP2) and ``*there should be much more consultation between Schiphol and the handlers at this level*'' (WP3). The workshop itself was experienced as a positive opportunity for operational and innovation stakeholders to shape a development direction together, something participants indicated they would value more of. The implementation condition is that the system must be developed together with the people who will use it, directly addressing the adoption risk identified as the dominant concern.
T4:	**Safe and workable behaviour**	Participants acknowledged that the system must stop immediately when obstacles are detected, but also that it must not stop unnecessarily. The Roboxi FOD detection robot was mentioned as a positive example: ``*it stops immediately if it can touch anything*'' (WP2). The implementation condition is that stop behaviour must be both reliable and operationally workable: the system must stop when it genuinely cannot proceed safely, but must not stop so frequently that ground handlers start bypassing it or losing trust in its ability to complete the task.

#	Tension decision	Explanation
T5:	**Building on existing digital infrastructure**	At task level, participants proposed using the VDGS for aircraft type recognition and as the primary trigger for the robot: ``*as soon as the VDGS shows the aircraft type, the robot knows where to go*'' (WP6). The implementation condition goes beyond this single integration: the autonomous connection system should build on existing digital infrastructure rather than introducing separate systems. This means leveraging the VDGS for task-level triggering and integrating with or extending the ROS system for broader airside coordination. At the coordination level, greater central visibility of planning between Schiphol and ground handlers is needed, to clarify who is expected where and when, and to manage the dependencies between tasks that the autonomous system relies on. The autonomous connection system is therefore not a standalone solution but an integrated component of the broader digital infrastructure being developed within the Autonomous Airside Operations programme.

Appendix K: Interactive roadmap hyperlink and feedback integration

Click to access the roadmap

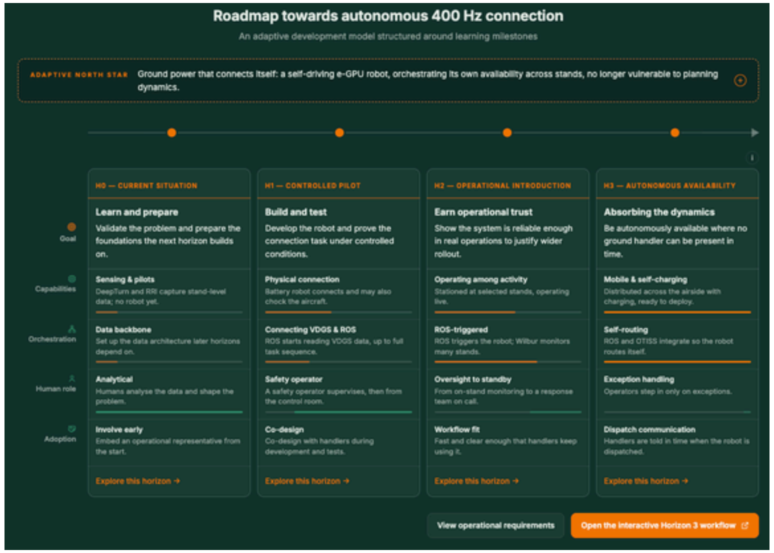


Roadmap towards autonomous 400 Hz connection

An adaptive development model structured around learning milestones

ADAPTIVE NORTH STAR Ground power that connects itself: a self-driving e-GPU robot, orchestrating its own availability across stands, no longer vulnerable to planning dynamics.

	H0 — CURRENT SITUATION	H1 — CONTROLLED PILOT	H2 — OPERATIONAL INTRODUCTION	H3 — AUTONOMOUS AVAILABILITY
Goal	**Learn and prepare** Quantify how much planning dynamics drive docking delays, and lay the groundwork the next horizon builds on.	**Build and test** Develop the robot and prove the connection task safely and reliably under controlled conditions.	**Earn operational trust** Show the system is reliable enough in real operations to justify wider rollout.	**Absorbing the dynamics** Autonomously available at the stand to connect where no ground handler can be present on time: solving the H0 problem.
System capabilities	**Sensing and pilots** DeepTurn and RRI capture stand-level data, and the marshal pilot reveals how the connection could be triggered.	**Physical connection** Battery-powered robot that connects and may also chock the aircraft, designed to scale to dynamic deployment.	**Operating among activity** Stationed at selected stands, functioning safely alongside other stand processes.	**Mobile and self-charging** Positioned across the airside with charging infrastructure, ready to deploy to any stand.
Orchestration	**Data backbone** Set up the DeepTurn, VDGS and ROS architecture the later horizons depend on.	**Connecting VDGS and ROS** ROS starts reading VDGS data, building up to trigger and full task sequence.	**ROS-triggered** ROS, fed by DeepTurn, triggers the robot; Wilbur gives the control room a multi-stand overview.	**Self-routing** ROS and OTISS integrate so the robot dispatches, routes and charges itself.
Human role	**Analytical role** Humans analyse the data and shape the problem, with ground handlers grounding it in stand-level reality.	**Safety operator in pilot** A safety operator at the stand, expanding to control-room oversight of task execution.	**From oversight to standby** From on-stand monitoring to dispatching a response team only when needed.	**Exception handling** Operators step in only on exceptions, as autonomous movement is phased in from control-room steering.
Adoption & co-development	**Early involvement** Embed an operational representative in the team from the start.	**Co-design** Involve handlers during development and the first tests, shaping the system with their feedback.	**Workable in practice** Quick and clear enough that handlers keep using it.	**Clear communication** Handlers know in time, through their own systems, when the robot is dispatched.
Development activities	**Analyse and prepare** Click to view the checklist	**Build and trial** Click to view the checklist	**Deploy and refine** Click to view the checklist	**Integrate and scale** Click to view the checklist
Progression criteria	**Ready to build** Click to view the checklist	Tr	checklist	**Availability proven** Click to view the checklist

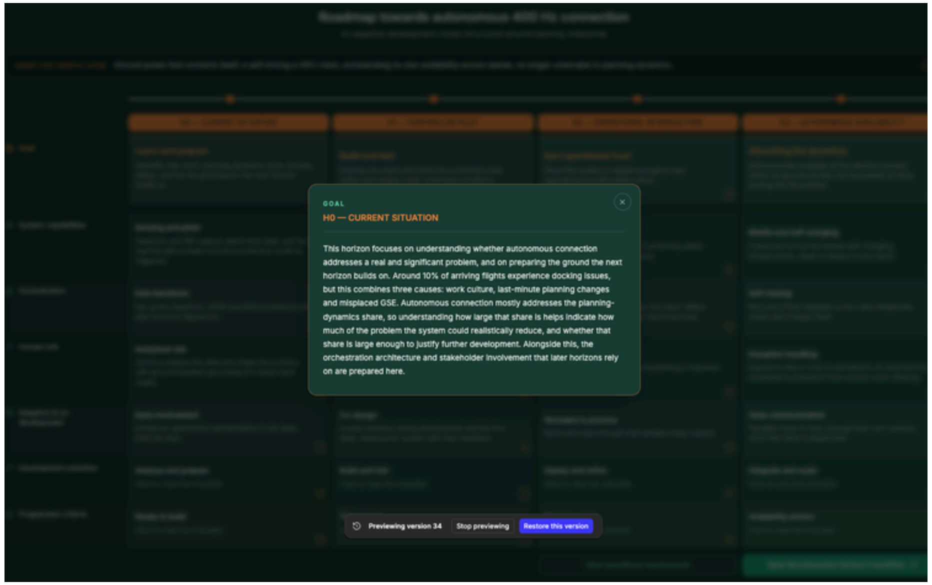


Roadmap towards autonomous 400 Hz connection

An adaptive development model structured around learning milestones

ADAPTIVE NORTH STAR Ground power that connects itself: a self-driving e-GPU robot, orchestrating its own availability across stands, no longer vulnerable to planning dynamics.

	H0 — CURRENT SITUATION	H1 — CONTROLLED PILOT	H2 — OPERATIONAL INTRODUCTION	H3 — AUTONOMOUS AVAILABILITY
Goal	**Learn and prepare** Validate the problem and prepare the foundations the next horizon builds on.	**Build and test** Develop the robot and prove the connection task under controlled conditions.	**Earn operational trust** Show the system is reliable enough in real operations to justify wider rollout.	**Absorbing the dynamics** Be autonomously available where no ground handler can be present in time.
Capabilities	**Sensing & pilots** DeepTurn and RRI capture stand-level data; no robot yet.	**Physical connection** Battery robot connects and may also chock the aircraft.	**Operating among activity** Stationed at selected stands, operating live.	**Mobile & self-charging** Distributed across the airside with charging, ready to deploy.
Orchestration	**Data backbone** Set up the data architecture later horizons depend on.	**Connecting VDGS & ROS** ROS starts reading VDGS data, up to full task sequence.	**ROS-triggered** ROS triggers the robot; Wilbur monitors many stands.	**Self-routing** ROS and OTISS integrate so the robot routes itself.
Human role	**Analytical** Humans analyse the data and shape the problem.	**Safety operator** A safety operator supervises, then from the control room.	**Oversight to standby** From on-stand monitoring to a response team on call.	**Exception handling** Operators step in only on exceptions.
Adoption	**Involve early** Embed an operational representative from the start.	**Co-design** Co-design with handlers during development and tests.	**Workflow fit** Fast and clear enough that handlers keep using it.	**Dispatch communication** Handlers are told in time when the robot is dispatched.
	Explore this horizon →	Explore this horizon →	Explore this horizon →	Explore this horizon →



GOAL

H0 — CURRENT SITUATION

This horizon focuses on understanding whether autonomous connection addresses a real and significant problem, and on preparing the ground the next horizon builds on. Around 10% of arriving flights experience docking issues, but this combines three causes: work culture, last-minute planning changes and misplaced GSE. Autonomous connection mostly addresses the planning-dynamics share, so understanding how large that share is helps indicate how much of the problem the system could realistically reduce, and whether that share is large enough to justify further development. Alongside this, the orchestration architecture and stakeholder involvement that later horizons rely on are prepared here.

Figure K.1: Earlier versions of the interactive roadmap, revised based on feedback

Roadmap prototype evaluation

The interactive roadmap prototype was reviewed by two innovators to gather feedback on its **clarity and usability**. Their input was grouped into the following themes and used to refine the prototype.

Clarity of terminology

- "Progression criteria" read as fixed requirements to meet, whereas they were meant as choices that still need validating against real conditions.
    - Renamed to "validation points", and reworked from checkboxes into a three-state toggle (to validate / refine / confirmed) that reflects the status of each point.

Seeing change at a glance

- It was hard to see what changes per horizon without reading all the text.
    - Changed the text for a "horizon task overview" showing which work streams run across the horizons, making the shift between phases visible without reading every cell.

Visibility of bottlenecks

- The main blockers in each horizon were not visible in the prototype.
    - Added a dedicated bottleneck section per horizon, categorised by type (technical, regulatory, organisational), each with its own icon.

Visual appeal and recognisability

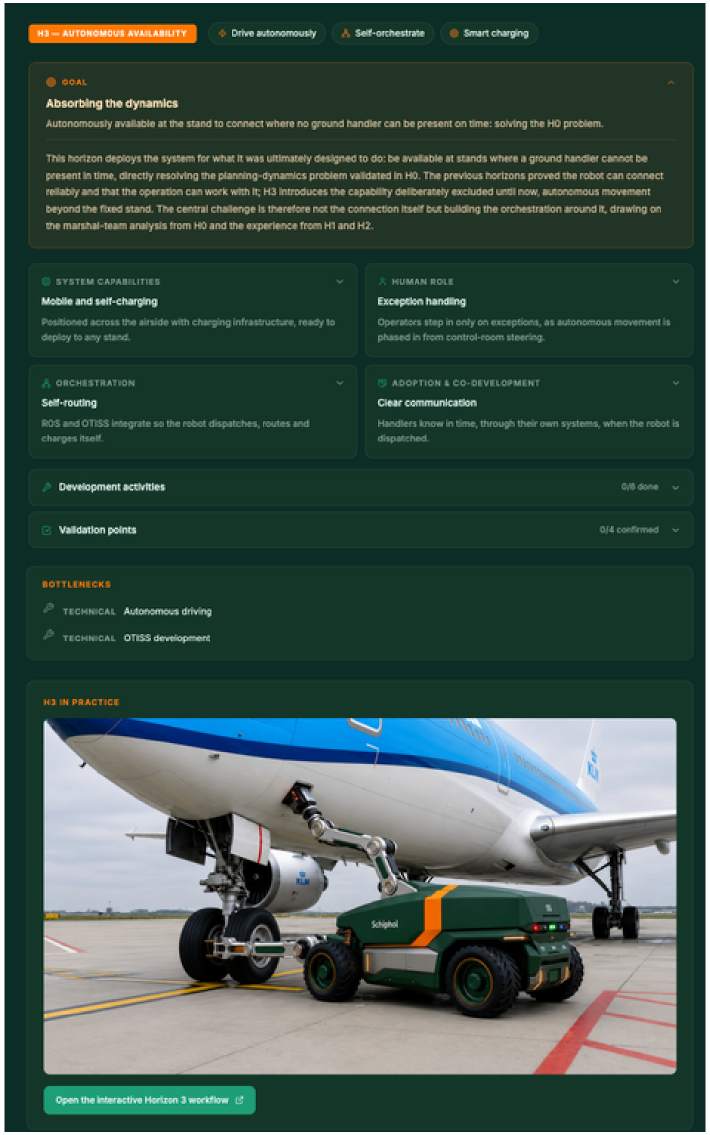
- Suggestion to add visuals so the roadmap is more attractive and easier to grasp at a glance, without first reading the text.
    - Added phase icons to each horizon header, and a subtle image of the autonomous robot connecting to the aircraft behind the title, so the topic is clear immediately.

Explanation for new users

- Suggestion to add a short, step-by-step guide for people new to the tool.
    - Added a "how to use this roadmap" guide.

Positive points and confirmed intent

- Both reviewers responded enthusiastically to the prototype overall, describing it as clear and well made.
- The interactive, clickable set-up was seen as a real strength, in particular the ability to tick off completed activities and track progress over time.
- The layered structure was appreciated: a high-level overview with the option to click through into the detail of each horizon.



GOAL

Absorbing the dynamics

Autonomously available at the stand to connect where no ground handler can be present on time: solving the H0 problem.

This horizon deploys the system for what it was ultimately designed to do: be available at stands where a ground handler cannot be present in time, directly resolving the planning-dynamics problem validated in H0. The previous horizons proved the robot can connect reliably and that the operation can work with it; H3 introduces the capability deliberately excluded until now, autonomous movement beyond the fixed stand. The central challenge is therefore not the connection itself but building the orchestration around it, drawing on the marshal-team analysis from H0 and the experience from H1 and H2.

SYSTEM CAPABILITIES

Mobile and self-charging

Positioned across the airside with charging infrastructure, ready to deploy to any stand.

HUMAN ROLE

Exception handling

Operators step in only on exceptions, as autonomous movement is phased in from control-room steering.

ORCHESTRATION

Self-routing

ROS and OTISS integrate so the robot dispatches, routes and charges itself.

ADOPTION & CO-DEVELOPMENT

Clear communication

Handlers know in time, through their own systems, when the robot is dispatched.

Development activities 0/6 done

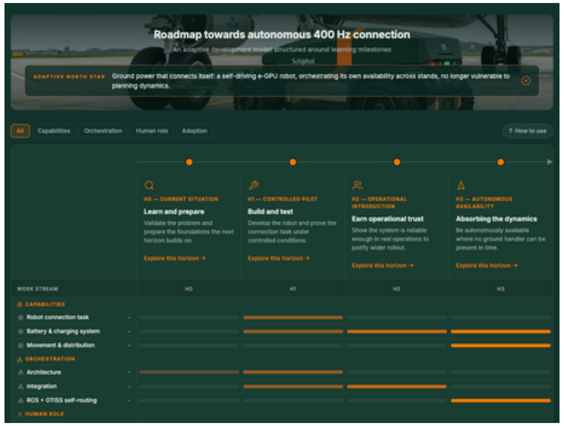
Validation points 0/4 confirmed

BOTTLENECKS

TECHNICAL Autonomous driving

TECHNICAL OTISS development

H3 IN PRACTICE



Roadmap towards autonomous 400 Hz connection

An adaptive development model structured around learning milestones

ADAPTIVE NORTH STAR Ground power that connects itself: a self-driving e-GPU robot, orchestrating its own availability across stands, no longer vulnerable to planning dynamics.

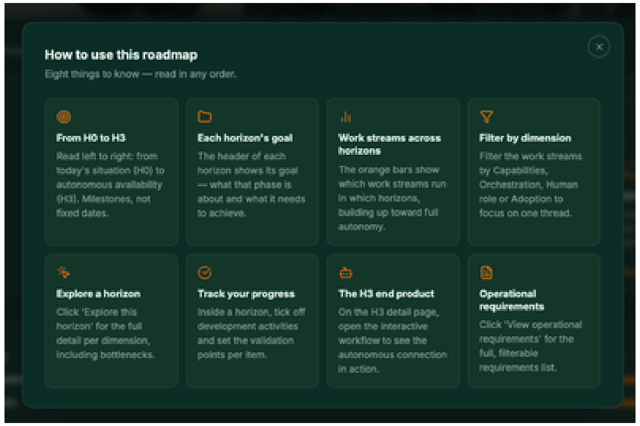
H0 — CURRENT SITUATION
Learn and prepare
Validate the problem and prepare the foundations the next horizon builds on.
Explore this horizon →

H1 — CONTROLLED PILOT
Build and test
Develop the robot and prove the connection task under controlled conditions.
Explore this horizon →

H2 — OPERATIONAL INTRODUCTION
Earn operational trust
Show the system is reliable enough in real operations to justify wider rollout.
Explore this horizon →

H3 — AUTONOMOUS AVAILABILITY
Absorbing the dynamics
Be autonomously available where no ground handler can be present in time.
Explore this horizon →

WORK STREAM	H0	H1	H2	H3
CAPABILITIES				
Robot connection task		▬		
Battery & charging system		▬	▬	▬
Movement & distribution				▬
ORCHESTRATION				
Architecture	▬	▬		
Integration		▬	▬	
ROS + OTISS self-routing				▬
HUMAN ROLE				



How to use this roadmap

Eight things to know — read in any order.

From H0 to H3
Read left to right: from today's situation (H0) to autonomous availability (H3). Milestones, not fixed dates.

Each horizon's goal
The header of each horizon shows its goal — what that phase is about and what it needs to achieve.

Work streams across horizons
The orange bars show which work streams run in which horizons, building up toward full autonomy.

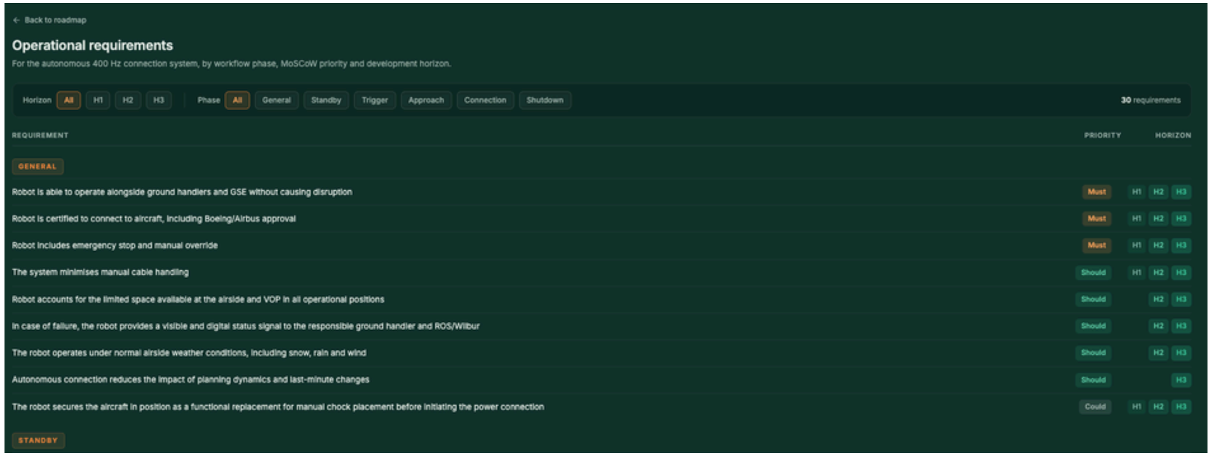
Filter by dimension
Filter the work streams by Capabilities, Orchestration, Human role or Adoption to focus on one thread.

Explore a horizon
Click 'Explore this horizon' for the full detail per dimension, including bottlenecks.

Track your progress
Inside a horizon, tick off development activities and set the validation points per item.

The H3 end product
On the H3 detail page, open the interactive workflow to see the autonomous connection in action.

Operational requirements
Click 'View operational requirements' for the full, filterable requirements list.



Operational requirements

For the autonomous 400 Hz connection system, by workflow phase, MoSCoW priority and development horizon.

30 requirements

REQUIREMENT	PRIORITY	HORIZON
GENERAL		
Robot is able to operate alongside ground handlers and GSE without causing disruption	Must	H1 H2 H3
Robot is certified to connect to aircraft, including Boeing/Airbus approval	Must	H1 H2 H3
Robot includes emergency stop and manual override	Must	H1 H2 H3
The system minimises manual cable handling	Should	H1 H2 H3
Robot accounts for the limited space available at the airside and VOP in all operational positions	Should	H2 H3
In case of failure, the robot provides a visible and digital status signal to the responsible ground handler and ROS/Wilbur	Should	H2 H3
The robot operates under normal airside weather conditions, including snow, rain and wind	Should	H2 H3
Autonomous connection reduces the impact of planning dynamics and last-minute changes	Should	H3
The robot secures the aircraft in position as a functional replacement for manual chock placement before initiating the power connection	Could	H1 H2 H3
STANDBY		

Figure K.2: Final version of the interactive roadmap