Multi-Operation Automated Vehicles for Aircraft Turnarounds

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by

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Thesis Green Light

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Preface

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AI Statement

For this report/article/work for the course ME-MME MSc Thesis (ME54035), I have used Generative AI to obtain inspiration for the overall structure of the report and to improve the grammar, style, layout, and/or spelling of the text. In all cases, I have reviewed and corrected the work and remain fully responsible for the content of the report.

Abstract

Due to poor working conditions caused by emissions, heavy workloads, and significant staff shortages, airlines and airports are turning towards automation for a solution. While many automation developments focus on turnaround management and scheduling, research on the automated execution of turnaround operations is lacking, especially within arrival and departure operations and on the usage of multi-operation vehicles. This study aims to determine whether combining multiple operations into a single autonomous platform is operationally and financially beneficial. Task dependencies and interconnections were modelled, allowing the simulation of interactions and propagation of delays. A financial model was then developed to quantify the impact of changes in turnaround durations on delay-related costs. Based on net present value, reliability, flexibility, and technological readiness, different automated concepts developed for each operation were assessed and compared with multi-operation automated platforms. Additionally, the effects of automation on the scheduling, spatial management, and communications during aircraft turnarounds were analysed, accompanied by a risk analysis. Findings from this study indicate that the automation of arrival and departure operations can provide operational gains and positive financial returns, provided reliability performance meets the required thresholds. Multi-operation platforms enhance flexibility significantly, but may under-perform in operational efficiency and financial viability. The results from this thesis provide an informed approach in automating aircraft turnarounds, supporting decision-making on automation concepts and accelerating the transition to an environment that ensures occupational health and safety for ground staff.

Nomenclature

Abbreviations

Abbreviation	Definition
UFPs	Ultrafine Particles
FOD	Foreign Object Debris
ORL	Operational Readiness Level
PBB	Passenger Boarding Bridge
LDL	Lower Deck Loader
APU	Auxiliary Power Unit
GPU	Ground Power Unit
E-GPU	Electric Ground Power Unit
PCA	Preconditioned Air
AI	Artificial Intelligence
TRL	Technology Readiness Level
AGV	Automated Guided Vehicle
D2D	Device-to-device
IoT	Internet of Things
PTZ	Pan-Tilt-Zoom
NPV	Net Present Value
RAMS	Reliability, Availability, Maintainability, and Safety

Symbols

Symbol	Definition	Unit
μ	Mean	[min]
σ	Standard Deviation	[min]
t	Time	[s] or [min]
I	Investment cost	[€]
N	Time horizon	[year]
R_t	Net savings per year	[€]
i	discount rate	[-]

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Introduction

1.1. Background and Motivation

Between the arrival and departure of an aircraft, various operations must be performed during a so-called turnaround. This includes refuelling, baggage (un)loading, and passenger boarding, as well as smaller operations such as placing wheel chocks and connecting the aircraft to a power unit. For this, many trucks will be driving on the ramp in a well-orchestrated dance. Unfortunately, however, the working conditions on the aircraft ramp are poor: Work is often too physically demanding, especially for baggage crew,[1][2] and the ultra-fine particles (UFPs) emitted by aircraft engines are bad for the health of ground personnel.[3] Next to this, there is a large shortage of ground operations staff.[4] This shortage in staff also increases the workload, further degrading the working conditions.

Due to these poor working conditions and the significant staff shortage, KLM has invested substantially in automating ground operations.[5][6] One of the operations that KLM is working on to automate is foreign object debris (FOD) detection. FOD detection is of paramount importance to prevent debris from damaging aircraft and potentially getting sucked into aircraft engines, causing significant damage. Currently, a ground operations staff member must check the aircraft ramp every time an aircraft comes in. To automate this, KLM has recently experimented with a robotic platform. The creation of such a robotic platform, however, raises the question of whether this robot can also help automate other ground operations, and if this is more efficient compared to separate solutions.

1.2. Problem Description

Although automated turnaround operation solutions have not yet been widely implemented, many different concepts for different turnaround operations are being developed to increase efficiency and improve the working environment, like the FOD detection robotic platform mentioned before. During current turnaround automation developments, however, each turnaround operation is approached individually. As such, solutions generated are specialised for one operation. Whilst this reduces the magnitude and investment since the developments get split into smaller portions, it also increases the number of systems required to perform an aircraft turnaround, which can lead to coordination problems and even congestion. An alternative could be a multi-operation system capable of completing multiple operations in the turnaround process. Unfortunately, the operational and financial impact of such a system is currently unknown, as well as how well it performs compared to single-operation systems.

1.3. Research Gap

Whilst many automation developments are done on turnaround management,[7][8][9][10][11][12][13] research on actual turnaround operations is lacking. Whilst some developments and research have been done on large-scale operations such as baggage handling [5] and automated taxiing,[14] as well as FOD detection,[15][16][17][18][19][20][21] very few, if any, developments have been done on other operations such as wheel chock placement and removal, cone placement and removal, and power and preconditioned air (dis)connection.[22] Some automated systems for similar operations exist outside of the aviation industry: for example, in the trucking industry, the use of rotating chocks [23] is already widely used. Similarly, automated cone placement is implemented for highway maintenance as well.[24] No research has been done on the potential implementation of these systems into the aviation industry, however. The gap in research on small-scale operations in the turnaround process leaves a very significant part of the turnaround process relying on manual labour. In fact, since many of these smaller operations occur at the start or end of the turnaround process, the impact the automation has on staffing is even larger than the other processes, as ground-staff can arrive later or leave earlier in the turnaround process. Additionally, the small amount of research and development that has been done focuses on single-operation solutions. Although this simplifies the development, it overlooks potential synergies that could come from combining multiple operations into a single system. Such a multi-operation system can also reduce vehicle congestion and simplify the coordination.

1.4. Research Objective

To fill the research gap mentioned, the automation of small-scale operations must be researched, and the performance of a multi-operation automated vehicle compared to specialised methods must be analysed. The use of such a vehicle can have secondary effects on the turnaround operation and thus might require several adjustments to other parts of the operation. Because of this, the implications such a vehicle has must also be investigated. To determine the performance of both the single- and multi-operation automated vehicles, several questions must be answered. Firstly, multiple automated vehicle concepts must be generated and broadly analysed to determine basic feasibility. To determine its performance, its financial impact, reliability, and other factors must be analysed. With this, the multi-operation concepts can then be compared to the best-performing single-operation concepts. After choosing the most effective multi-operation automated vehicle concepts, the best combination of single- and multi-operation concepts can be analysed even further on the effect on scheduling, coordination, and spatial planning of an aircraft turnaround, allowing a proper analysis of the full automation and its implications on turnaround operations. To determine the further steps required for implementation, both a risk and operational readiness level (ORL) analysis must be performed as well, bridging the gap between concept and implementation.

1.5. Research Questions

From the research objective, the main research question and sub-questions addressed in this thesis can be set as follows:

Main research question:

How do multi-operation automated systems compare to single-operation automated systems in aircraft turnaround, and what are the implications for turnaround operations?

To answer this question, the following research sub-questions will need to be answered first:

Sub-Questions:

1. What are the key operations involved in aircraft turnaround operations, and how are they currently scheduled and managed at airports?
2. How can the financial impact of changes in turnaround time be modelled and quantified?
3. Which combination of single- and multi-operation automated concepts provides the best potential performance?
4. How would an automated arrival and departure process affect ground handling activities, and what are the key operational risks?

1.6. Scope

To maintain focus and ensure feasibility within the available time frame, the scope of this thesis is set as follows:

- Only ’under the wing’ turnaround operations will be considered. ’Above the wing’ operations, such as bridge connection and (de)boarding, are omitted due to an automated vehicle being unable to reach the cabin. Similarly, only operations that take place on the ramp are considered.
- Due to the research gap in automation of small-scale operations mentioned earlier, only the operations occurring at the arrival and departure phase of the turnaround will be analysed.
- A detailed mechanical, electrical or structural design will not be provided, nor will prototypes be made, due to the limited available time.

- Due to the urgency of automating the turnaround process and unpredictability of immature technologies, only technologies and systems with a technology readiness level of 5 or higher will be considered.
- The aircraft and ramp types considered will be limited to the aircraft and ramps used by KLM for commercial aviation.
- Due to the severe differences between airport infrastructures, when analysing the infrastructural readiness and infrastructural changes required, the infrastructure of Schiphol Airport will be considered.

1.7. Methodology

To address the research questions, the study is divided into four phases, as shown in Figure 1.1.

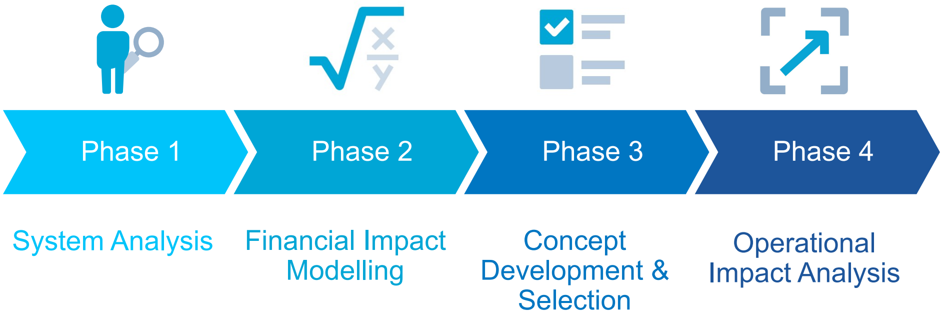

Figure 1.1: Thesis Phases

The thesis will consist of the following 4 phases: System Analysis, Financial Impact Modelling, Concept Evaluation & Selection, and Operational Impact Analysis. Each phase will correspond to a report chapter and research sub-question. Below, each phase and its methodology are further explained.

Phase 1: System Analysis

Before automated concepts can be evaluated, the current methods of aircraft turnaround must be analysed. With this, the automated concepts can be compared with the current process, giving an estimate of their performance. The literature study done previously, which focused on aircraft turnaround automation and its operational and scheduling implications in general, will provide a strong basis for this. That said, more literature and data will need to be gathered to allow a more thorough analysis and to provide more information on topics that were only explored superficially. The literature research for this thesis will be conducted through a review of industry reports, existing research, and regulatory guidelines related to airport operations. Relevant sources will be gathered from, for example, Google Scholar, Scopus, IEEE Xplore, organisations such as ICAO, IATA, and airport operators. Next to this, more information and data are gathered through observation and documentation of turnaround processes at Schiphol in person. In this phase, the research sub-question 1: ”What are the key operations involved in aircraft turnaround operations, and how are they currently scheduled and managed at airports?” will be answered.

Phase 2: Financial Impact Modelling

In this phase, research sub-question 2: ”How can the financial impact of changes in turnaround time be modelled and quantified?” will be answered. Before automated concepts can be evaluated and compared, the financial impact of a reduction or increase in turnaround time must be evaluated. To achieve this, data must be gathered on the current duration of tasks, after which a model needs to be created that calculates the financial impact of a change in turnaround time.

Phase 3: Concept Development and Selection

This phase will cover the development of multiple design concepts for both single- and multi-operation concepts, the evaluation of the concepts, and the comparison of them using trade-off matrices. The most suitable combination of solutions will then be selected for further analysis in the following phases. During this phase, research sub-question 3: ”Which combination of single- and multi-operation automated concepts provides the best potential performance?” will be answered.

Phase 4: Operational Impact Analysis

In this phase, the selected solution will be analysed further through the following smaller studies:

- A scheduling study, analysing the effect that the automated systems have on the operational schedule used in aircraft turnarounds.
- A spatial analysis, analysing the spatial deployment of the automated systems, and the effect on congestion on the ramp.
- A human-robot interaction study, looking into the effects the robot will have on human operators and how the robot should communicate its intent and anomalies to ground personnel.
- A robot-robot interaction study, looking into the communications and data transfer methods the robots can use to transmit and share data.
- A study into the malfunctions and repairs of the chosen automated systems and the use of remote control as a semi-automated solution or as a method to solve anomalies
- A risk analysis, identifying potential hazards and uncertainties present in the chosen concepts. In this analysis, technical, operational, and safety-related risks will all be analysed and given an impact, severity and total risk rating. Through this total risk rating, the most serious risks present can be found.

The combination of these studies will answer research sub-question 4: ”How would an automated arrival and departure process affect ground handling activities, and what are the key operational risks?”

After the phases are completed and the research sub-questions answered, the main research question, ”How do multi-operation automated systems compare to single-operation automated systems in aircraft turnaround, and what are the implications for turnaround operations?”, can be answered.

2

System Analysis

According to Fricke and Schultz [25], around 10% of aircraft delays originate from delayed ground operations. Furthermore, around 30% is from rotation (delay propagation), thus around 14% of aircraft delays truly originate from delayed ground operations. With a total delay cost in the US alone in 2007 of 31.2 billion US dollars, this equates to a cost of 4.3 billion US Dollars for delays caused by ground operations.[26] With such a massive impact, proper management and scheduling of ground operations is vital. The schedule should be flexible to allow for unforeseen circumstances and cushion delays, whilst at the same time being as short as possible to minimise aircraft downtime. In this chapter, the first research sub-question: ”What are the key operations involved in aircraft turnaround operations, and how are they currently scheduled and managed at airports?” will be investigated. First, the operation schedule will be analysed, starting with the operational dependencies and their flow structure. After this, the current scheduling methods used to prevent delays and the communication methods will be discussed. Finally, the current usage of AI and predictive scheduling will be explored.

2.1. System definition

Before the operations within the turnaround process can be analysed, the full system and its actors must be defined and set. The turnaround process can be defined as the combination of all operations occurring on the ramp, as seen in the visual representation of a turnaround in Figure 2.1, where it is demarcated by the red outline. From this, the following actors can be identified:

- The aircraft
- Ground personnel
- Passengers and flight crew
- Passenger boarding bridge
- Catering vehicles
- Passenger luggage and cargo
- Baggage carrier
- Baggage loaders
- ULD loaders
- Fuelling vehicle
- Boarding stairs
- Cleaning vehicle
- Water service vehicle
- Toilet service vehicle
- Pushback truck
- Wheel chocks
- Safety cones
- Ground power unit
- Preconditioned air unit
- Fuel pit
- Air start unit
- Turnaround control system

These actors form the operational environment in which the automation can be implemented. With these actors identified, this gives a structured overview to analyse their interactions and dependencies.

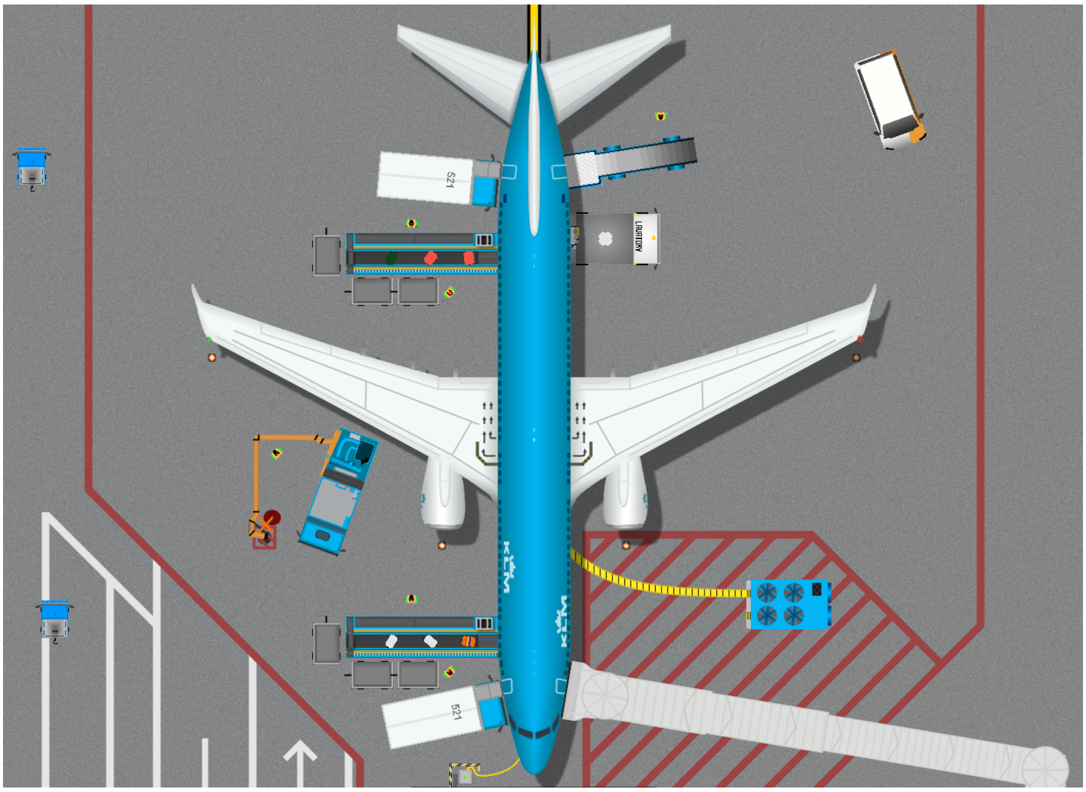

Figure 2.1: Visual representation of the turnaround process[1]

2.2. Turnaround Operations

To schedule the different operations within a time frame, the dependencies of the operations need to be known. From the KLM 737 operation manual [27] and the 737 turnaround GOMS [28], the different operations and their dependencies can be derived. Below, 6 different main paths within the turnaround operations can be found with their nominal completion time: Technical operations, refuelling, water and toilet services, baggage handling (front and rear), and passenger services. For all the operations in these paths, the previous operation in its path must be completed first, and the times are based on 737-800 operations. In some cases, several operations are performed in parallel. These are denoted by a '+' sign. It should be noted that all operations within a group must be completed before the next operation can be started. From these main paths and the information from the manual, GOMS, and interviews with KLM staff, a full flow chart can be made. In Figure 2.2, this full flow chart of the turnaround operations can be found. Here, the arrows denote the operational dependencies, and the red line follows the critical path according to the 737 turnaround GOMS [28]. Clearly, many alternative paths are possible, which can interact with each other and thus cause delays. On the next page, the different paths and their nominal duration are described.

As can be seen from the different path durations, the front baggage loading and passenger services take up the most time, whilst, for example, the water and toilet services take the least. It should be noted that whilst the front baggage handling can take up to 57 minutes, the cargo holds are often not full, and the baggage handling takes a lot less time than assigned. This is also why the passenger services pathway is deemed the critical path. Any delays in this path will directly result in a departure delay, whilst delays in other paths can be cushioned until the nominal + delay time exceeds the 57 minutes required by the critical path. Alternatively, this also means that any improvements made within the critical path will be directly noticeable in turnaround time. For this study, and thus for the following sections, only the operations occurring in the arrival and departure process as seen in Figure 2.2 and as discussed in section 1.6 will be investigated further.

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[1] github.com/TimGioHog/JIP_ApronSim

1. Technical Operations Path - Total Duration: 47 minutes + slack time

Chocks + GPU + Cones	→	Technical Inspection	→	Remove GPU	→	Attach Tug + Front Chocks	→	Rear Chocks + Walkaround	→	Pushback
2 min		34 min		1 min		1 min		2 min		7 min

2. Refuelling Path - Total Duration: 47 minutes + slack time

Chocks + GPU + Cones	→	Refuel Prep & Deboard	→	Refuel	→	Refuel Finalising	→	Remove GPU	→	Attach Tug + Front Chocks	→	Rear Chocks + Walkaround	→	Pushback
2 min		14 min		6 min		14 min		1 min		1 min		2 min		7 min

3. Water and toilet Services Path - Total Duration: 18 minutes + slack time

Chocks + GPU + Cones	→	Water Service and Toilet Service	→	Remove GPU	→	Attach Tug + Front Chocks	→	Rear Chock + Walkaround	→	Pushback
2 min		5 min		1 min		1 min		2 min		7 min

4. Baggage Handling Path (Rear) - Total Duration: 52 minutes + slack time

Chocks + GPU + Cones	→	Connect Rear LDL	→	Offload Rear	→	Load Rear	→	Remove LDL Rear + Attach Tug + Front Chocks	→	Rear Chocks + Walkaround	→	Pushback
2 min		2 min		13 min		25 min		2 min		1 min		7 min

5. Baggage Handling Path (Front) - Total Duration: 57 minutes

Chocks + GPU + Cones	→	Connect Front LDL	→	Offload Front	→	Load Front	→	Remove LDL Front + Attach Tug + Front Chocks	→	Rear Chocks + Walkaround	→	Pushback
2 min		2 min		18 min		25 min		2 min		1 min		7 min

6. Passenger Services Path - Total Duration: 57 minutes

Chocks + GPU + Cones	→	Connect Bridge	→	Deboard	→	Cabin Cleaning + Catering + Cabin Prep	→	Boarding	→	Flight Closure + Rear Chocks + Walkaround	→	Pushback
2 min		2 min		7 min		13 min		22 min		4 min		7 min

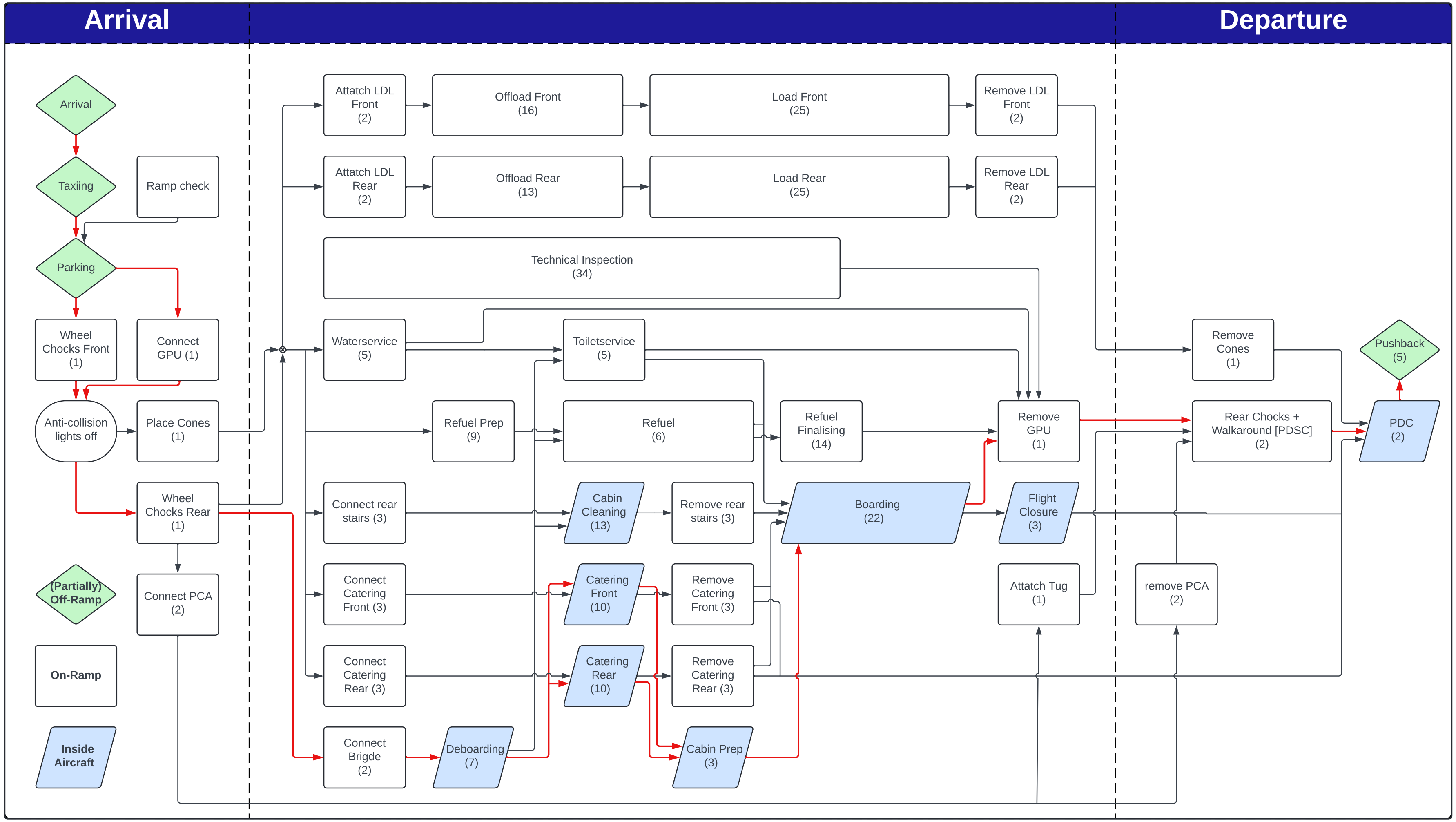

Figure 2.2: Hierarchical flow chart of turnaround operations with the critical path in red. Green diamond-shaped blocks indicate (partial) off-ramp operations, and blue parallelograms indicate operations occurring inside the aircraft.

2.3. Current Systems Used

To further understand the turnaround operations and to be able to evaluate the new automated methods, the current systems used to complete an aircraft turnaround must be known. In this section, the different operations considered and the current method to complete them are explored. Since the focus will be on operations that are performed at the start and end of the turnaround, the scope for this study will be limited to the following operations: FOD Check, Wheel Chock placement, Connecting GPU, Connecting PCA, Cone Placement, and Technical inspection (walkaround).

2.3.1. Wheel Chock Placement

The first thing that happens once the aircraft is stationary is the placement of the chocks. These chocks hold the aircraft in place, even in windy conditions or on slightly sloped ramps. The chocks are installed at the nose gear and at the main landing gear, as seen in Figure 2.3.[27] In heavy wind conditions, extra chocks might need to be installed.[27] When placing the chocks, a small gap of around 5 cm, depending on the aircraft type, must be left to prevent unnecessary loading. The front chocks can be placed immediately, but the rear chocks can only be placed after the anti-collision lights are shut off. This is because the engines must be fully stationary before the rear chocks can be placed. After the engines are shut off by the pilots, the anti-collision lights are turned off. After installing both the front and rear chocks, the landing gear brakes can be released. Currently, the chocks are placed manually. Whilst there is plenty of time to place the front chocks, due to the engines still spinning at that point, the placement of the rear chocks slightly delays the operation, on which all other operations are fully dependent. Because of this, this delay directly causes a delay in the overall turnaround time as well. The chocks are removed by the pushback truck driver, who removes the front chocks when attaching the pushback truck and usually removes the rear chocks during the final walk-around. With a mass up to around 35 kg for a large chock pair, the manual placement of chocks can, especially when large chocks are needed for larger aircraft, cause significant strain for the ground staff.

Figure 2.3: Wheel chocks placed around a nose landing gear.[2]

2.3.2. Power Connection

To ensure that an aircraft does not need to run its auxiliary power unit (APU) to power itself while parked, a ground power unit (GPU) or shore power is used, saving fuel consumption, emissions and noise. After placing the front wheel chocks, the aircraft is connected to the GPU or shore power unit via a cable near the nose landing gear.[27] Presently, the GPU or shore power is manually connected. There are three different supply methods: through a jet bridge-mounted unit, a mobile GPU, or a fixed unit.

Jet bridge-mounted GPU

When a jet bridge is available, a jet bridge-mounted unit can be used, which can also use shore power. Because they are mounted on the jet bridge, the cable does not take up extra space or restrict vehicle movement. A jet bridge with a GPU unit can be seen in Figure 2.4.

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[2] en.wikipedia.org/wiki/Wheel_chock#/media/File:Chocks.JPG

Figure 2.4: Jet bridge with PCA and GPU units[3]

Figure 2.5: E-GPU Connected to an aircraft [29]

Mobile GPU

For remote gates or gates without jet bridges, a mobile GPU as seen in Figure 2.5 is often used. These carts can be moved next to the aircraft and are manually connected. Although these mobile GPUs can be used for all kinds of aircraft, the movement of the cart does cost extra time. Some larger aircraft will also need multiple mobile GPUs to supply enough power. A large advantage of mobile GPUs is that they are relatively inexpensive. Currently, mobile GPUs are often diesel generators, creating additional emissions. In 2022, 73 of the 128 gates at Schiphol Airport used shore power, whilst the other 55 used mobile GPUs. In the same year, tests with E-GPUs that use battery power instead of conventional diesel generators were performed.[29]

Fixed GPUs

To allow remote gates without jet bridges to use shore power, a fixed GPU must be installed. Whilst these do allow the use of shore power, a fixed GPU requires a long distance to be traversed via cable, since these cannot be placed as close to the aircraft parking spot. To combat this, a ground power pit can also be used. By burying the fixed GPU in the ground, it can be connected to the aircraft quickly without the need for a long cable. An example of this can be seen in Figure 2.6. Such a pit is, however, very expensive due to the need to break open the ramp and lay underground cables when installing it.

Figure 2.6: Ground power pit[4]

2.3.3. Preconditioned Air

The air conditioning system of an aircraft is dependent on the aircraft's APU. Because the APU is switched off whilst parked, the aircraft's air conditioning system will also be turned off. To still provide a comfortable environment within the cabin, the aircraft is often connected to a preconditioned Air (PCA) unit. Similarly to power, preconditioned air can be delivered through a system on the jet bridge, a mobile unit, or via a fixed system, as seen in Figure 2.4, Figure 2.7, and Figure 2.8, respectively.

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[3] aviationpros.com/gse/gpus-pcas-power-carts-accessories/article/21265589/pca-hose-extending-and-retracting-made-easy

[4] aviationlearnings.com/utility-pit-systems/

Figure 2.7: Mobile PCA unit[5]

Figure 2.8: PCA Pit[6]

2.3.4. Cone Placement

Before service vehicles are allowed to approach the aircraft, cones must be placed to prevent accidental collisions with the aircraft. Before the cones can be placed, the anti-collision lights on the aircraft must be turned off by the pilots, and the aircraft engines must be fully shut down. From the 737 manual from KLM: ”Safety cones must be positioned max. 1 metre outward from each wing tip and maximum 1 metre in front of each engine. It is recommended to position additional safety cones a maximum of 1 metre behind tail or in front of nose when the aircraft is parked on an open ramp adjacent to a service road or if no markings exist.”[27] In Figure 2.9, the cone placement for the KLM Boeing 737 can be seen. Note that the blue cones shown here are only placed on remote ramps and, therefore, usually skipped. For wide-body aircraft, 2 cones are placed per engine, but none are placed underneath the wingtips. As of now, the cones are placed manually by one of the ground personnel. Whilst easy, it is quite time-consuming due to the large distances that need to be walked, especially for larger aircraft.

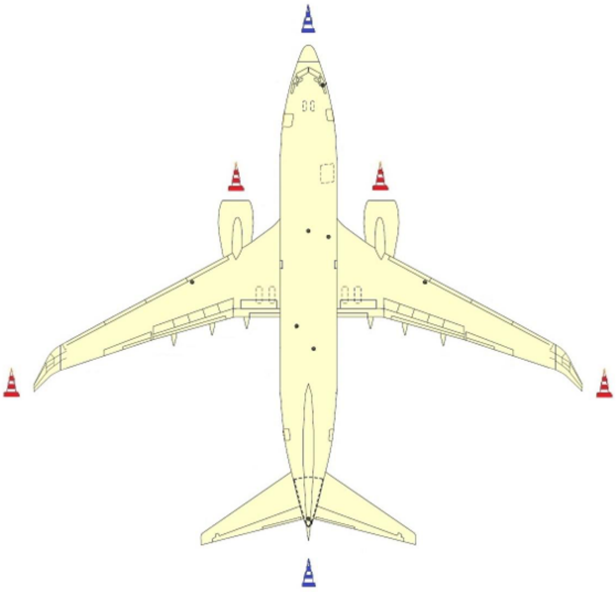

Figure 2.9: Cones 737 KLM Manual, with in red next to the tips and in front of the engines the mandatory safety cones, and in blue in front and behind the aircraft the additional safety cones[27]

2.3.5. Technical Inspection

During an aircraft turnaround, the aircraft must be thoroughly checked to identify any damage, leaks or other issues. This ensures the aircraft is safe and airworthy before departure. Technical inspections are performed by certified technicians from the maintenance department. He or she visually inspects the aircraft and its key systems. In Figure 2.10, the route taken by the technician can be seen. On this route, the key systems inspected can also be seen, such as the engines and flaps. Before pushback, the pushback driver must also perform a similar visual

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[5] mercurygse.com/resources/post/enhancing-passenger-comfort-and-efficiency-mercurys-cutting-edge-aircraft-preconditioned-pca-solutions

[6] aviationlearnings.com/utility-pit-systems/

inspection of the aircraft, also known as a walkaround.

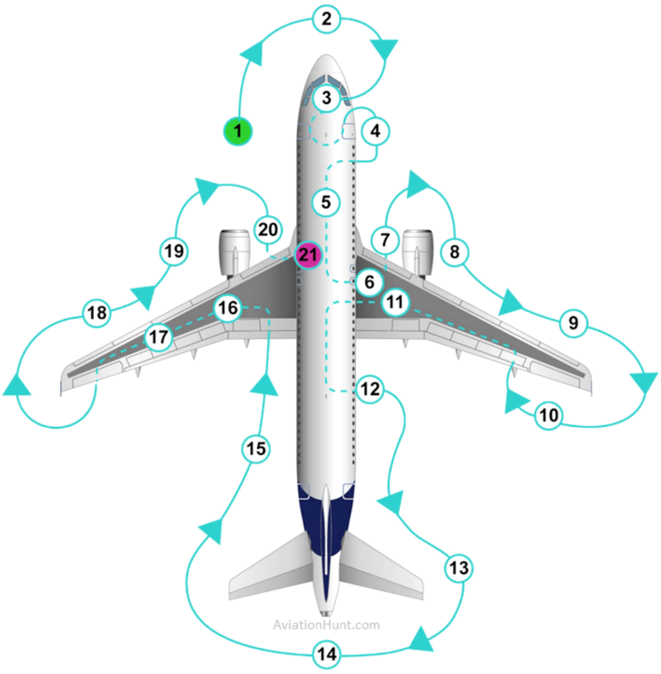

Figure 2.10: Technical inspection walking route.[7]

2.3.6. FOD Check

Before an aircraft arrives, the ramp must be checked for foreign objects, such as screws, tools, or pieces of clothing, but also pieces of broken pavement and wildlife. If not properly checked, such debris as seen in, for example Figure 2.11, could damage equipment or, in some cases, even cause injuries. Damage caused by FOD costs the aircraft business around $4 billion (US) every year, or around $26 per flight in aircraft repairs, plus $312 in indirect costs.[30][31] Around 55% of FOD damage occurs at the stand, even with current prevention methods.[32] This makes applying new technologies that minimise this very attractive. As of now, ramps are manually checked by personnel present. The employee performing the check can then also immediately remove the debris from the ramp. Whilst this is an easy job, it is time-consuming and not infallible, as humans can sometimes fail to spot debris or neglect this operation when experiencing high workloads.

Figure 2.11: A mechanic's tool left behind[21]

2.4. Scheduling with Delays

In real-world conditions, the actual duration of operations often differs from the scheduled time. For example, when looking at the boarding times of A320 aircraft with an arrival delay of 5 to 10 minutes, the duration roughly follows a normal distribution, as seen in Figure 2.12.[25] It is clear that this operation has a significant standard deviation from the mean. This makes scheduling quite difficult since unused buffer time is expensive, and departure delays are as well. Furthermore, the boarding time depends greatly on how many passengers travel with the aircraft.

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[7] aviationhunt.com

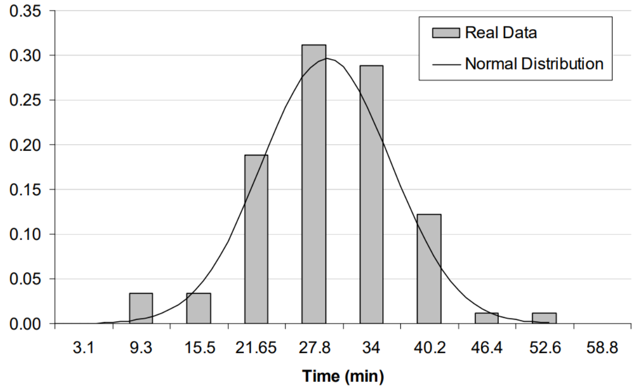

Figure 2.12: Boarding operation times with an arrival delay of 5-10 minutes (μ = 32.5, σ = 7.9, n = 90) [25]

Table 2.1: Boarding operation statistics by arrival delay [25]

	Arrival Delay (min)					
	0-5	5-10	10-15	15-20	20-25	25-30
μ	36.52	32.51	28.68	26.83	28.96	24.98
σ	11.01	7.86	6.43	4.76	7.41	8.31

The passenger count cannot be known when planning the flight; however, this results in unused expensive ground time when fewer passengers than expected travel, or causes delays when more passengers travel than expected. Since delays are more expensive than buffers, mainly due to delay propagation to other flights, significant buffers must be present in the schedule to mitigate delays and minimise delay propagation. Buffers can be placed both within and between operations. In Table 2.1, the boarding operation statistics for different arrival delays can be seen.

Clearly, the amount of time required for the operation reduces with arrival delay, even though the number of passengers boarding does not change. This effect is mostly present due to the usage of buffers within the operation, minimising the delay propagation to the next flight. The effect of buffers can also be seen by looking at the starting times of different operations. In Figure 2.13, the different start times for boarding, fuelling, catering, cleaning, and deboarding can be seen for different arrival delays. The effect is easily visible, with boarding often finishing 10 minutes earlier when the aircraft has a significant arrival delay.

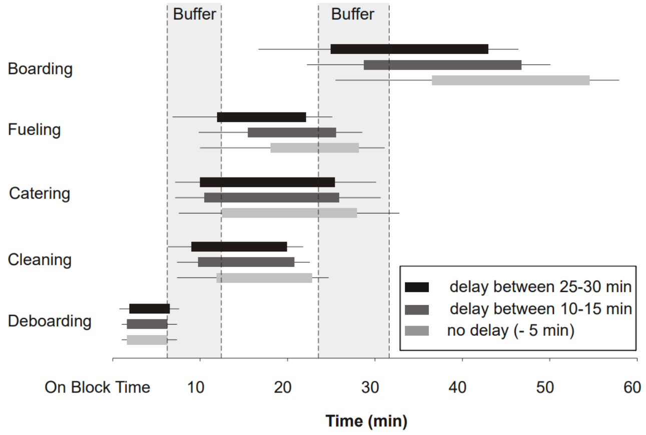

Figure 2.13: Operation start times and duration with different arrival delays [25]

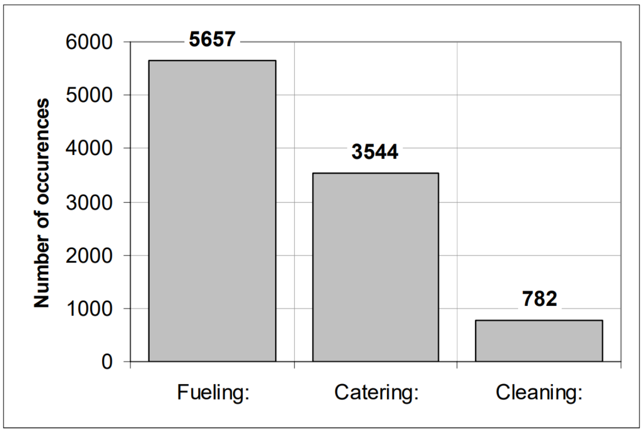

Figure 2.14: Distribution of limiting operations linking passenger deboarding/boarding and baggage unloading/loading [33]

With these distributions and buffers in the turnaround operations, it becomes unclear if the passenger services path discussed in section 2.2 is in fact always the critical path. To determine the critical path, Schultz and Fricke [33] ran Monte Carlo simulations to determine the level of reliability in today's turnaround operations. Here, the 3 main operations running in parallel between passenger deboarding/boarding and baggage unloading/loading were analysed, the results of which can be seen in Figure 2.14.

From these results, it is clear that in most of the cases (56%), the refuelling path was actually most critical. Based on interviews with ground handling personnel and observations done by Fricke and Lehmann [34], the distortions in the fuelling operation are mostly due to obstructions from other service vehicles, which then result in a delayed starting time or the safety requirements not being met. Secondly, the fuel computer sometimes struggles to calculate the precise filling quantity due to temperature variations. This causes the flow rate to be lower than for the other tanks and the centre tank to be opened too late. The distortions in the catering operation are again mostly due to obstructions from other service vehicles. Especially with smaller aircraft with bulk load, where the loading equipment is often in the way. Moreover, the purser needs to knock on the aircraft door after arriving in position to signal for the aircraft door to be opened. Sometimes, however, the crew does not notice this knock, causing a delay at the start of the operation.

2.5. Scheduling Communication

With the amount of operational dependencies shown in section 2.2, communication between ground personnel performing the different operations is vital. For example, the drivers of the fuel and catering trucks need to receive a signal from the colleague connecting the GPU and placing the wheel chocks so that they can approach the aircraft. This can be done through several methods: Manual, such as hand gestures and vocal, Radio, and Electronic, such as tablets or signal lights. The use of Artificial Intelligence (AI) in communication, such as computer vision and/or predictive methods, will be discussed in the following sections.

2.5.1. Manual Communication

Manual communication, such as hand gestures or verbal communication, is still used extensively during ground operations. One example of this is aircraft marshalling, where ground personnel communicate with the pilot(s) of an aircraft using visual signalling. The marshal can also give signals to other ground personnel, for example, to start placing the wheel chocks. This type of communication, however, has several downsides: during periods of poor visibility, the signals might not be visible to the pilots or ground crew. Whilst self-illuminating wands can be used as seen in Figure 2.15, these can still be hard to see during heavy fog or rain.

Figure 2.15: A long exposure of the usage of marshalling wands, directing a SH-60F Sea Hawk to take off

Despite efforts to standardise the signals used, the hand signals used often differ per country. For example, for aircraft marshalling, the North Atlantic Treaty Organisation [35], the International Civil Aviation Organization [36], and the Federal Aviation Administration [37] all use different standards, which can cause confusion and therefore disruptions and incidents. Due to the amount of noise generated by aircraft and other vehicles on the apron, verbal communications without the use of electronic devices such as headsets will often not be heard or misinterpreted.

2.5.2. Radio Communication

Since the 70s/80s, headsets have been increasingly used for ramp communications. These headsets allow ground personnel to talk with each other without having to be face-to-face, and reduce noise with the incorporation of speakers in the hearing protection. With modern wireless headsets, such as the ones from dbdcommunications [38] and Airbus Critical Communications [39], the usage has become even more flexible. Modern headsets also have high noise attenuation, making communications clearer in a noisy environment. The main downside of radio communication is radio clutter, which can cause delays or miscommunications.

2.5.3. Electronic Communication

With the emergence of software and other electronic devices, ground operations scheduling has become even more flexible. For example, Austria's Vienna Airport uses Panasonic TOUGHBOOK laptops, as seen in Figure 2.16, to improve ground operations.[40]

Other companies, such as SotenGroup [41] or Rugstorm [42] have been developing similar rugged tablets. With these tablets, operations can be electronically signed off, notifying not only ground personnel but also higher management. This data can also be stored, which can later be used for an in-depth analysis, for example, on delay correlation.

Figure 2.16: Panasonic TOUGHBOOK used at Vienna Airport [40]

Figure 2.17: A computer vision algorithm detecting and monitoring different vehicles [11]

2.6. Computer Vision

With the recent developments in AI, computer vision can be used to track turnaround operations, instead of manually communicating start and end times as discussed before. Using one or several fixed cameras mounted on a gate pointed at an apron, images can be taken of the current situation on the apron. Using computer vision, vehicles used in operations can be identified and tracked, as seen in, for example Figure 2.17.

Using computer vision, for example, it can be determined that the fuelling of a vehicle is completed once the fuel or hydrant truck used in the operation leaves the apron. In Table 2.2, several studies and their descriptions can be found that investigated this method. It should be noted that it is not possible to use the cameras used in these studies to monitor the progression of operations occurring inside the aircraft, such as passenger deboarding, catering, cleaning, and finally, passenger boarding. Since 2023, Schiphol has been implementing this method using what they call Deep Turnaround.[13] According to Schiphol: "The Deep Turnaround algorithm detects and reports over 70 unique turnaround events in 30 turnaround processes. It detects delays as early as 40 minutes before the targeted off-block-time, and helps to make informed decisions." Next to 52 stands at Schiphol, Deep Turnaround has also been partially implemented at Eindhoven Airport and at Edinburgh Airport in Q1 2025.

Table 2.2: Computer vision studies performed for turnaround operation improvements

Related work	Description
Lu et al. (2016) [7]	Detection and monitoring of several turnaround operations such as aircraft arrival, pushback and the start of taxi, for which machine learning and computer vision methods are used on video surveillance data. This data is obtained through cameras mounted on the gate.
Van Phat et al. (2020) [8]	Monitoring of several turnaround operations, through object and activity detection, and object tracking. Also makes predictions on pushback time and recognises different aircraft types. Uses convolutional neural networks, which are based on a video-analytic framework. Collects data and detects activity in real-time using live camera feeds.
Gorkow (2020) [9]	A deep learning based detection approach to detect turnaround operations and vehicles.
Wang et al. (2020) [43]	A real-time kinematic tracking device and heading units improving ground support handling by tracking equipment, allowing improved scheduling and collision detection of turnaround equipment.
Wang et al. (2021) [10]	A real-time onboard positioning and heading system to monitor the location and velocity of turnaround equipment, with a focus on multi-carriage logistics trains. Uses model-based tracking and geometry-based recurrence.
Yildiz et al. (2022) [11]	Deep learning and computer vision are used to detect and timestamp turnaround operations actions, using a single fixed camera.
Thai et al. (2022) [12]	Computer vision for surveillance and management of aircraft taxiing and turnaround operations using convolutional neural networks. Also predicts pushback time and detects aircraft types.

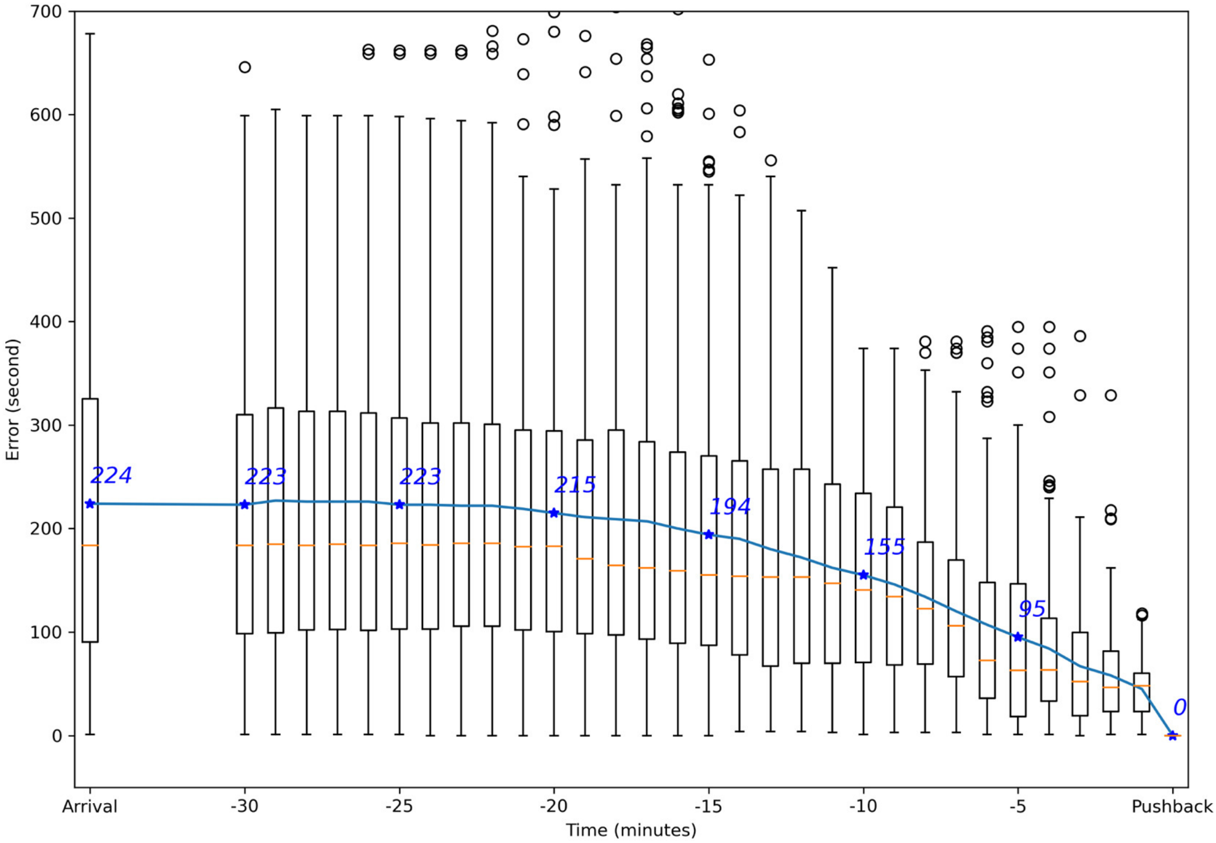

Figure 2.18: Statistical Push-back prediction error throughout a turnaround [12]

2.7. Predictive Scheduling

With an increasing amount of data on the starting and completion times of operations, better predictions can be made for completion times of other operations and potential delays. For example, if the boarding bridge is connected 4 minutes later than scheduled, the chances of a departure delay are much higher. With manual or radio communication methods discussed previously, this data will often not be passed on to higher airport management, making them unable to respond to the increased risk. With the usage of electric communication, such as tablets or computer vision, this data can be transferred instantly to airport management. For instance, Schiphol saw a reduction in last-minute gate changes of 25% due to the predictive features of Deep Turnaround.[13] Similarly, Van Phat et al. [8] and Thai et al. [12] from Table 2.2 made prediction algorithms that continuously made predictions on the pushback time of the aircraft. This pushback time prediction will get more accurate when approaching the pushback, as can be seen in Figure 2.18. Here, the mean error at arrival would be the same prediction error when no prediction algorithm is used.

2.8. Conclusion

In this chapter, the second research sub-question: ”What are the key operations involved in aircraft turnaround operations, and how are they currently scheduled and managed at airports?” was investigated. First, all operations and their dependencies were identified, from which it was found that the passenger services and front baggage loading paths took up the most time, whilst the water and toilet service consumed the least. Next to this, a hierarchical flow chart was made to identify complex dependencies and relations, which can be found in Figure 2.2. After this, the current systems used to perform these operational tasks were investigated. From this, it can be concluded that practically all operations are done almost fully manually. Whilst sometimes some operations, such as GPU and PCA connection, are eased with the use of, for example, mobile units, they still require manual connection to the aircraft. After integrating delays and time distributions, it was found that the refuelling path was most critical in 56% of the cases, demonstrating the unpredictability of the operation durations and delays. To gain a better understanding of how these schedules were managed, the communication methods used were explored, after which the use of AI and computer vision to communicate could be investigated. From this, it is clear that the usage of computer vision to communicate operational starting and completion times can significantly improve turnaround performance. The usage of digital communication also allows for predictive scheduling, mitigating the impact of potential delays.

3

Turnaround Efficiency Impact Modelling

To assess the performance of different concepts, the financial impact of an increase or decrease in task duration should be modelled. In this chapter, the financial effect of decreasing or increasing delays due to the decrease or increase of turnaround time will be investigated, and sub-question 2: "How can the financial impact of changes in turnaround time be modelled and quantified?" will be answered.

With a significant reduction in turnaround time, the schedule of an aircraft can be adjusted so that it can make an extra flight on a day. Smaller aircraft, such as an Embraer E190STD, can make between 6 and 8 flights on a day, resulting in 5 to 7 turnarounds. Since a short flight takes at least around 40 minutes, a total turnaround time reduction of at least 6 minutes is needed before an extra flight is possible. For larger aircraft, this becomes even larger, due to the longer, and thus fewer, flights they make. Since the operations discussed in chapter 4 take significantly less time, the value of adjusting the allocated turnaround time is negated. Instead, the value of a reduction (or cost of increase) in departure delays will be analysed, whilst assuming that the allocated times for turnarounds stay the same. For example, if the departure process duration is reduced by a minute, a delayed aircraft would have a 12-minute delay instead of the 13-minute delay it would have had. Even a reduction of 10 seconds will have an effect. Whilst the reimbursement fees might, for example, be calculated by minute or even 30 minutes, this does not matter due to the small reduction having the potential of reducing the delay below said threshold. Whilst this will then, of course, happen a lot less often, the effect will then be much larger, meaning that the average effect is unaffected by such thresholds or rounding.

Since the effect of a small reduction in turnaround time on staffing is very small, this effect will also be neglected. It should be noted that for the trade-offs made in chapter 4, when evaluating the different concepts for an operation, any small financial effect from a reduction in staffing would be shared by all concepts, as they are all fully automated and therefore have no effect on the comparison made. In short, only the savings generated through shortened delays are analysed.

3.1. Model Overviews

To calculate the total savings generated by decreasing the turnaround time, a model as seen in Figure 3.1 is created. Here, the light blue blocks are inputs, and the green block on the right is the output. First, the time improvement on the total turnaround time is calculated by subtracting the new estimated turnaround time from the current turnaround time. After this, the following procedure is done for each flight within the KLM flight database: First, the flight delay is extracted by comparing the scheduled departure time with the actual departure time. After this, the cost of the flight delay is calculated by finding the cost of the delay extracted earlier. These two steps are done again for the new estimated flight delay, where the flight delay is reduced by the time improvement in turnaround time. This can be done, since the allocated time is assumed to be the same, resulting in an extra margin the size of the time improvement. With the original cost of the flight delay and the new cost of the flight delay, the savings created for the flight can be calculated. Doing this for each flight and summing up the savings results in the total savings generated from the time improvement. In case the turnaround takes longer and the time improvement is negative, the same model can be used to calculate the added cost, which is then represented by the savings being negative.

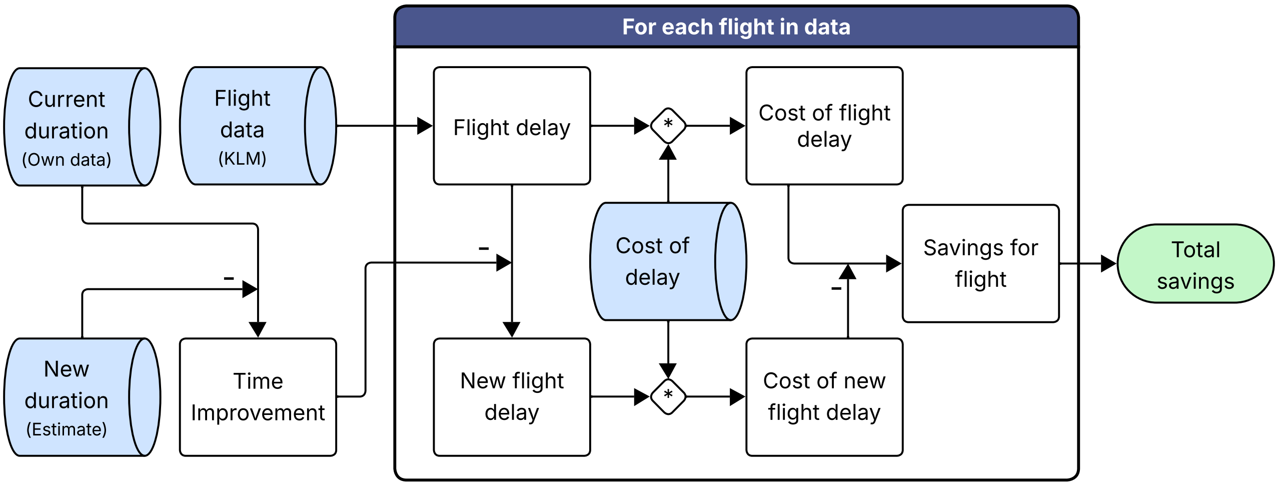

Figure 3.1: Model 1 overview (blue cylinder = input, green oval = output)

To reduce the heavy computational load from performing these operations on hundreds of thousands of flights, flight delay data from the literature can be used as well. In this case, the model shown in Figure 3.2 can be used, where a probability density function can be created for the delays. With this, the relative cost graph can be calculated (average cost for each flight vs delay) by multiplying the cost of each delay by its probability. Summing up the relative costs of all delays considered will result in the total cost. To calculate the total savings, the new total cost can be subtracted, which can be calculated through a new probability density function with reduced delays.

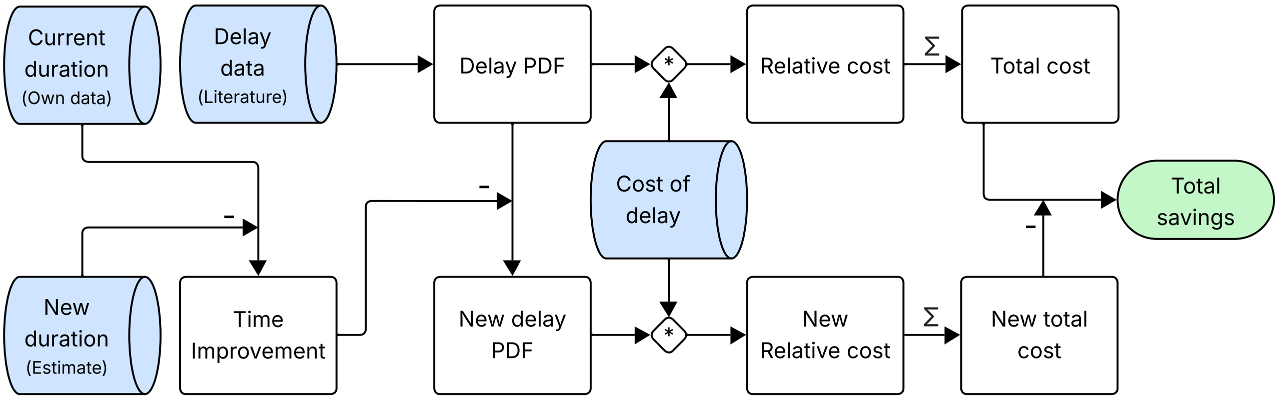

Figure 3.2: Model 2 overview (blue cylinder = input, green oval = output)

The algorithms underlying these models are implemented in Python, of which the code can be found in Appendix C as well as on GitHub.

In the following sections, the different inputs are discussed in further detail, as well as the relative cost step from model 2 and the results in total savings.

3.2. Current Duration

To assess how much faster or slower an automated version is of an operational task, the current duration must be known first. Unfortunately, the only data available was from idealised schedules such as the GOMS[28] or from timestamps entered by turnaround coordinators, which are unusable due to the often incorrectly timestamped tasks.

Both of these were also marked in minutes, whilst smaller tasks such as chock placement would often take less than 30 seconds. This meant that new data had to be gathered to get an idea of the task durations in seconds. This also gives the added benefit of extra time spent watching and learning about the turnaround process. A sample of the data gathered can be seen in Table 3.1 below. Here, the S means start time, E end time, and D the total duration of the task. All of which are in seconds. The moment the aircraft becomes stationary is set as t=0. Some data is missing due to the accidental omission of a timestamp. It should be noted that for the end time, the return walk from performing a task is included. For example, when measuring the duration of cone placement, both the walk to and back from the wingtip are included.

Table 3.1: Sample data with task start times, end times, and durations in seconds

Aircraft Type	Chock Front S	Chock Front E	Chock Front D	Chock Rear S	Chock Rear E	Chock Rear D	GPU S	GPU E	GPU D	Cones Left S	Cones Left E	Cones Left D	PCA Used
E190	2	11	9	45	72	27	2	28	26	74	104	30	Yes
E190	0	7	7	62	85	23	0	18	18				Yes
A320-232	20	33	13	20	49	29				56	85	29	No
B737-MAX-9	16	26	10	28	57	29	43	69	26	118	155	37	No

In total, data from 31 different turnarounds was manually gathered, including both arrivals and departures. Whilst such a limited data size gives some uncertainty, it does give a better estimate to the duration. Whilst it could improve the analysis, gathering more data is very time-consuming and therefore not practical for this study.

3.3. Delay Frequency

To calculate the effect a reduction will have on delay costs, the departure delays must be known. For model 2, the departure delay distribution found by Fricke et al.[25] can be used, which can be seen in Figure 3.3. For model 1, all KLM flights between 1-1-2023 and 23-7-2025 can be used, from which their delays can be calculated by taking the difference between the scheduled departure time and the actual departure time. For comparison purposes, a probability density function can be created as well, which can also be seen in Figure 3.3. From this graph, it is clear that the data from the literature lacks delays above 60 minutes. Furthermore, the data from Fricke et al. is also notably lower than expected around a departure delay of 30 minutes.

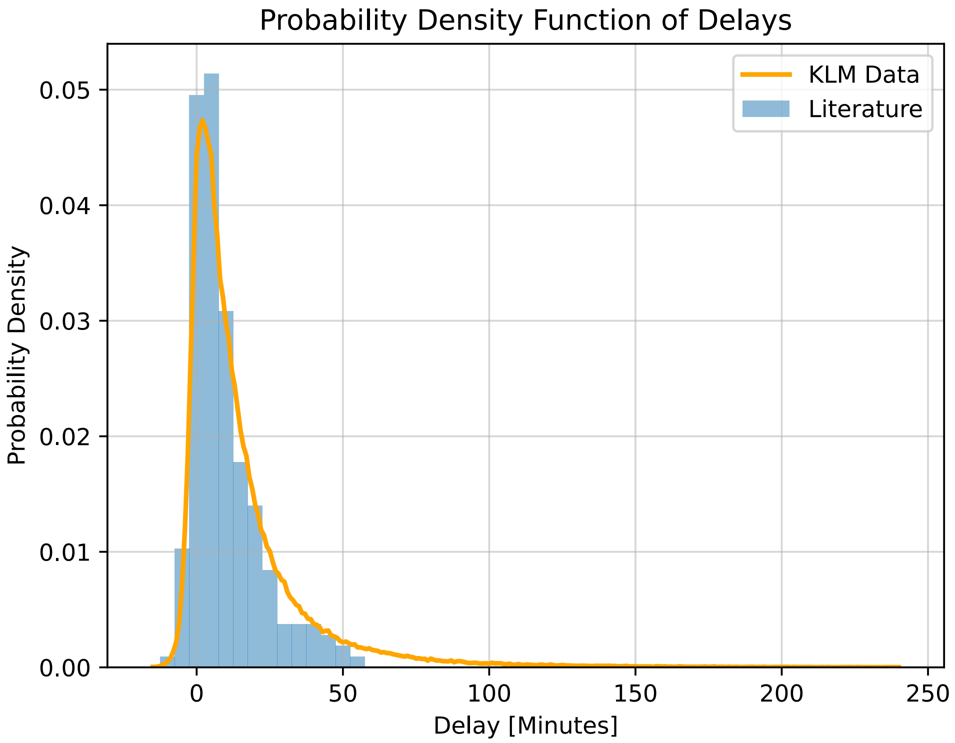

Figure 3.3: Probability Density Function of departure delays for KLM from 2023 to July 2025 and from Fricke et al.[25]

As seen in Figure 3.4, the departure delays will depend on the aircraft type used. From this, it can, for example, be seen that smaller aircraft such as the E7W (Embraer E175 used as a cityhopper with 7̃6 passengers) and 73W (Boeing 737-700 with 1̃26 passengers) have significantly shorter delays on average than larger aircraft such as the 77W (Boeing 777-300ER with 3̃81 passengers). This is somewhat to be expected, as larger aircraft also have longer turnaround times.

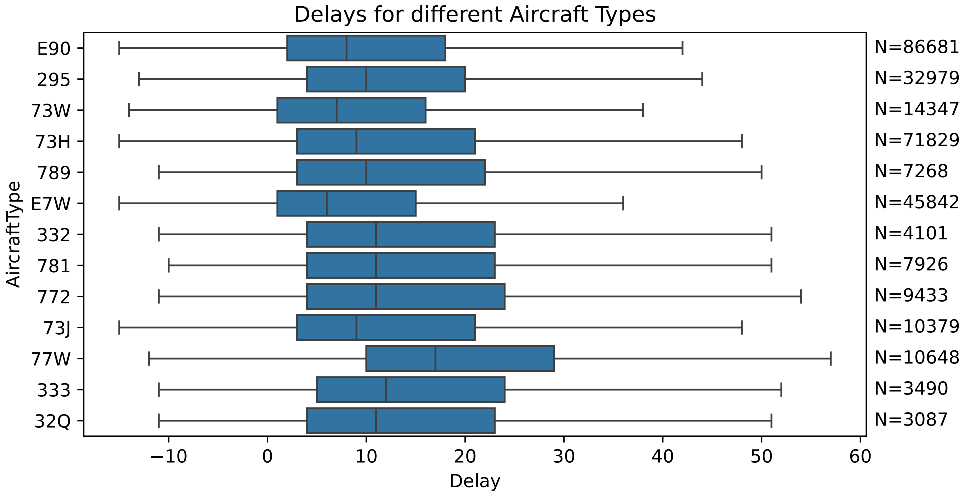

Figure 3.4: Departure Delay Boxplots for different Aircraft Types

For different ramps, the aircraft types used will differ significantly. For example, the B20 gate will mostly see smaller cityhoppers, whilst a gate at the E pier will see much larger aircraft. When making the value calculations, model 1 can adjust for this by filtering on specific gates; however, model 2 cannot, resulting in some error.

3.4. Delay Cost

Next to the frequency of departure delays, their cost must also be known. From a report made by the Department of Transport Studies, University of Westminster, London,[44] the average costs of delays for different aircraft can be found. In addition to direct costs, this report also considers indirect costs, including the expenses incurred due to subsequent delays resulting from the original delay. For this study, the at-gate delay costs are considered, since this corresponds with the departure delays discussed earlier. The table with costs for different aircraft and departure delays can be found in Table 3.2. This data was also validated by manually comparing it to several delay costs from actual flights and cost models used by KLM to predict the delay costs of a flight. These cost models are not directly used in this study due to the required manual extraction of data from these models. In Figure 3.5, a partial visual representation of the data shown in Table 3.2 can be seen.

Table 3.2: Costs in Euro for different aircraft and departure delays[44]

Delay(mins)	5	15	30	60	90	120	180	240	300
B733	60	360	1290	5780	15710	29730	39990	53720	71300
B734	70	400	1430	6510	17820	33670	45260	60680	80310
B735	60	330	1170	5200	14120	26740	36020	48490	64570
B738	70	440	1580	7200	19730	37270	50050	66970	88410
B752	80	520	1900	8780	24170	45610	61150	81610	107330
B763	150	880	3130	14510	39380	84200	119910	149510	186220
B744	220	1230	4440	20760	56480	120940	172030	213950	265480
A319	60	370	1310	5960	16330	30880	41560	55820	74070
A320	70	410	1490	6800	18680	35280	47420	63530	84020
A321	70	470	1770	8150	22490	42460	56980	76140	100320
AT43	30	160	520	2160	5730	10940	15040	20900	29020
AT72	40	190	670	2900	7780	14800	20160	27630	37690

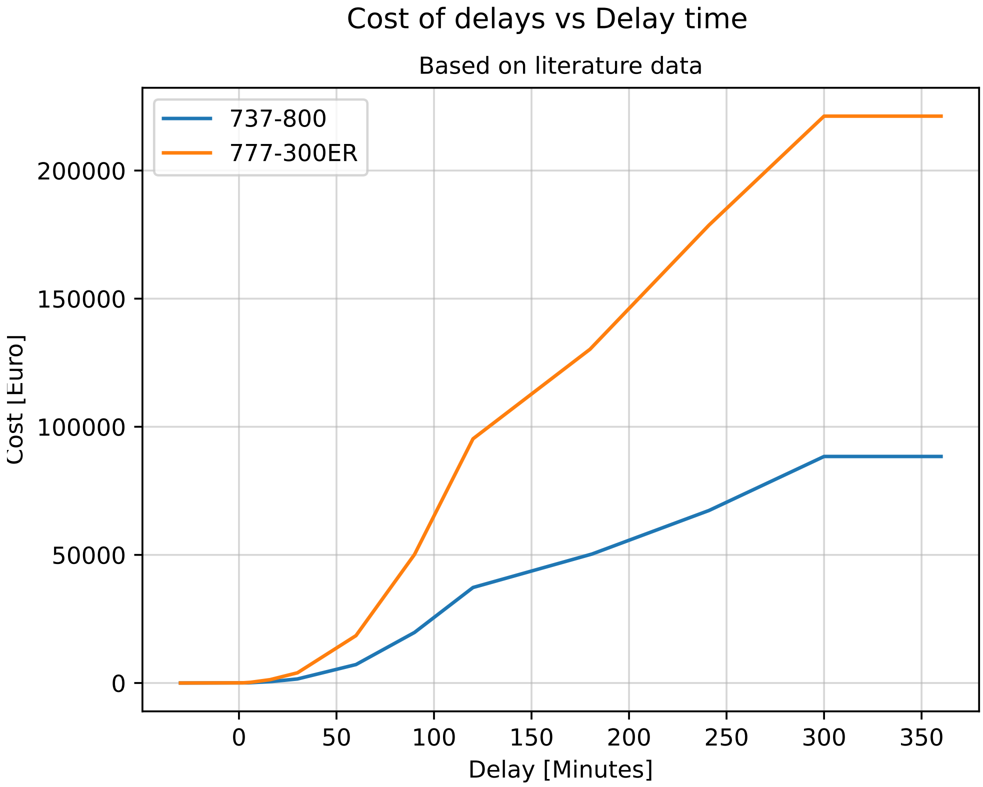

Figure 3.5: Average departure delay costs for B737-800 and B777-300ER aircraft [44]

For model 1, several aircraft used by KLM are not present in Table 3.2. As such, missing aircraft types must be matched to aircraft types in Table 3.2 that are similar. For larger differences, the costs are multiplied by the ratio on difference in passenger capacity. For example, the 77W type is translated to the costs of a B744, multiplied by the passenger ratio of 550/660. All aircraft type adjusted delay costs can be found in the code in Appendix C.

For model 2, the delay costs of the B738 type were taken, as seen in Figure 3.5, as this is a somewhat average aircraft type. This is, of course, a large approximation and will result in some error. To reduce this, the ratio of aircraft types flown can be extracted from the KLM data. From this, an average cost can be calculated and used instead.

3.5. Relative Cost

For model 2, the relative cost can be calculated by multiplying the cost of delays from Table 3.2 with the probability density function of delays shown in Figure 3.3. This gives a graph that shows the average cost of departure delays as seen in Figure 3.6 in blue. For better comparison, a relative cost graph has also been made from the data of model 1 and added to Figure 3.6. From the graph, it can be seen that 50-minute delays cost the most on average in both models. From the model 1 data, it is clear that small delays below 5 minutes and large delays above 200 minutes cost the least due to their low absolute cost and low frequency, respectively. It also shows that even though delays above 100 minutes are very rare, they still contribute significantly to the total delay costs. In the data from model 1, the lower frequency around 30 minutes and the lack of delays above 60 minutes are clearly visible, meaning that the usage of the data from Fricke et al. [25] is not suitable for these calculations, as it will severely underestimate the total cost.

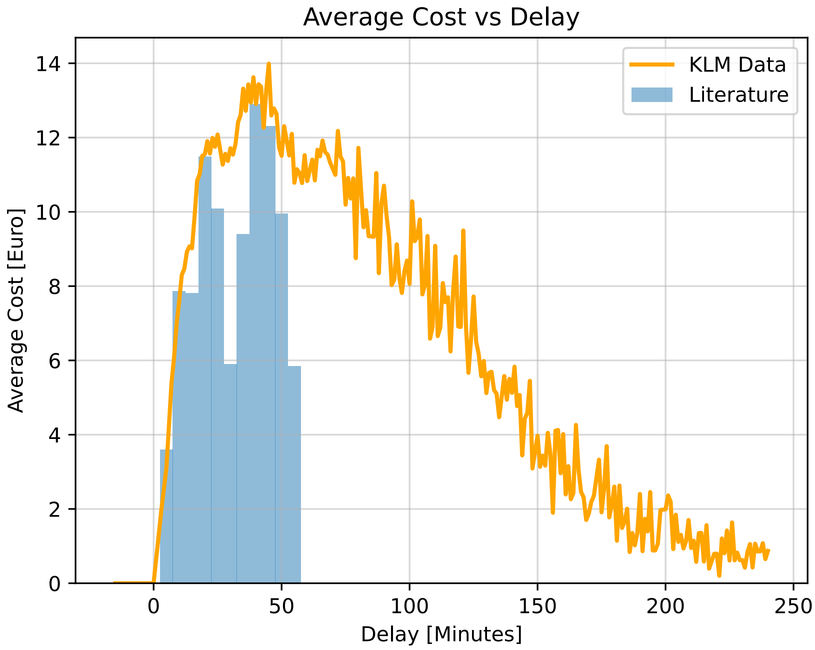

Figure 3.6: Average costs of delays

3.6. Total Savings

With the current duration, delay frequency, and cost of delays known, the total savings can be calculated for different new duration values. To visualise this, the difference in total costs can be plotted against different margin values, which can be seen in Figure 3.7. For example, if a margin of 10 minutes is created (by decreasing the turnaround time by 10 minutes), the difference in cost will be around €-600.

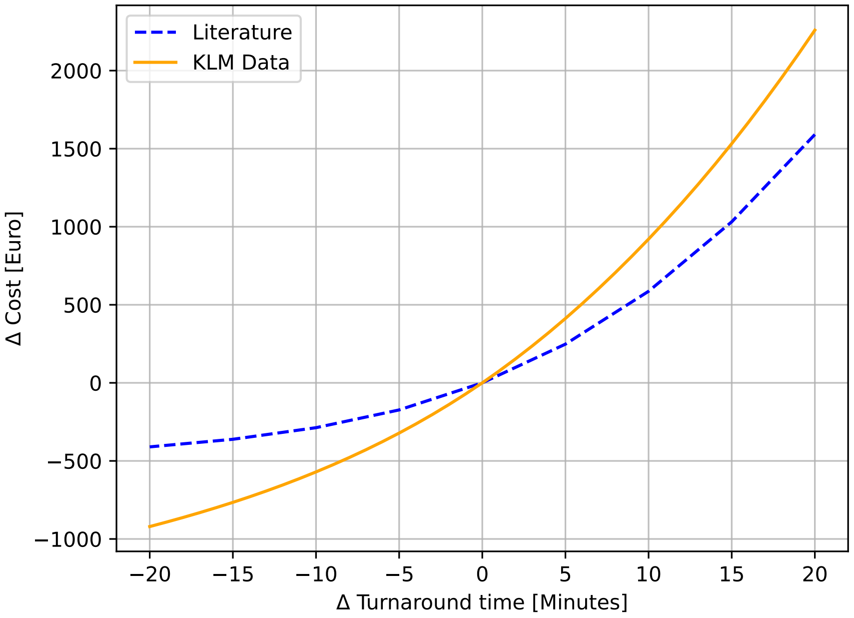

Figure 3.7: Change in delay costs due to a change in turnaround time

From this graph, it can be seen that, as expected, the value slowly flattens out with increasing margin due to there being no value of negative departure delays. It can also be seen that the data from model 2 is insufficient, as it severely underestimates the difference in cost. Since the automated solutions will likely not cause a very significant difference in turnaround time, the slope of the graph around the origin is the most important. This equates to around €70.33 per minute or €1.17 per second per flight for model 1.

3.7. VOP Specific Value

As mentioned in section 3.3, the pier or VOP also affects the departure delays. For example, when only using the flights from VOP B20, which only accommodates small cityhopper aircraft, the value equates to €34.8 per minute or €0.58 per second per flight due to the lower average delays from this VOP. That said, the number of flights is also higher due to the lower turnaround times. With an average of 3074 flights per year from this VOP, this equates to €1788 per year per second. A VOP that accommodates larger aircraft, such as E04, has a value of €177.94 per minute or €2.97 per second per flight due to the increased cost of a delay on a larger aircraft. That said, this VOP also only accommodates an average of 716 flights per year, resulting in a value of €2122 per year per second. This also means that if the costs of implementation on B20 and E04 are equal, it is financially more attractive to implement it at E04 first. In case the implementation costs are different, a calculation should be made to determine the best option.

3.8. Conclusion

In this chapter, research sub-question 2: ”How can the financial impact of changes in turnaround time be modelled and quantified?” was investigated. For this, two models were created that can calculate the cost or value of an increase or decrease in turnaround time. The algorithms underlying these models were implemented in Python, of which the code can be found in Appendix C as well as on GitHub. It was determined that model 2, which uses data from literature, severely underestimates the total impact and is therefore not usable. This also means that even though model 1, which uses data from KLM, is significantly more computationally heavy, it is the model that will be used to perform the calculations in chapter 4. With the difference in turnaround time and the gates that should be considered, the value or cost per year can now be easily calculated. It was determined that, depending on the aircraft types a ramp commonly services, between €34.8 and €177.94 can be saved on average per flight for every minute the turnaround time is reduced.

4

Concept Development and Selection

To understand how automation can be applied to aircraft turnaround, different concepts will need to be developed, analysed, and finally, a selection needs to be made between the different options available. As such, in this chapter, research sub-question 3 is investigated: Which combination of single- and multi-operation automated concepts provides the best potential performance?

As identified in chapter 2, the following main operations exist for an aircraft turnaround:

- Wheel chock placement
- Connecting Ground Power Unit (GPU)
- Connecting Preconditioned Air (PCA)
- Cones placement
- Passenger Boarding Bridge (PBB)
- Technical inspection
- Baggage (un)loading
- Rear Stairs placement
- Parking
- FOD check
- Cleaning service
- Water service
- Toilet Service
- Refuelling
- Catering
- Boarding
- Flight Closure
- Walkaround
- Pushback
- Taxiing

As mentioned in section 1.6, the scope for this study will be limited to the operations occurring at the start and end of the turnaround process and below the wing. These are: Wheel Chock placement, GPU Connection, PCA Connection, Cone Placement, Technical inspection, and FOD Check. Note that the technical inspection operation is taken instead of the walkaround operation due to their extreme similarity. A concept that can perform the technical inspection operation will also be able to perform the walkaround at the end of the turnaround. For each of these operations, the current systems used will be investigated, after which possible automated alternatives will be explored. The automated alternatives will be developed through a combination of the use of literature, own concepts, brainstorming sessions with KLM colleagues, and finally, conversations with external companies. A trade-off table will be made for each operation, using a decision matrix as described by Pugh.[45] To improve readability, not every aspect will be discussed for each concept. Instead, a full justification for the values given in the decision matrices is given in Appendix B. For each trade-off, a sensitivity analysis will be performed as well, to show if a small change in criteria weights or grading would result in a different concept being chosen. An adjustable Excel file with all the trade-offs can be found on GitHub, where scores or weights can be adjusted manually if as desired. After a single-operation selection has been made for all operations, Multi-operation concepts will be developed and compared with the selected single-operation concepts chosen earlier. Finally, the best combination of single-operation and multi-operation automated concepts will be chosen, answering the research sub-question.

4.1. Selection criteria

As mentioned, the single-solution concepts will be selected using decision matrices as described by Pugh.[45]. For each operation, the concepts will be weighed on the Net Present Value, the RAMS (Reliability, Availability, Maintainability, and Safety), the flexibility of servicing different aircraft types and stands, and finally the technology readiness level (TRL). Safety and environmental impacts will not be taken into account in these trade-offs, as all automated systems will need to be deemed as safe as current systems, as well as environmentally friendly. These will therefore be seen as a requirement, rather than a performance metric. Similarly, all concepts are assumed to be fully automated and require no human intervention during nominal operations. Therefore, staff reduction is not considered as a criterion either. Whilst other criteria, such as scalability, could be considered, they are considered unimportant compared to the four criteria mentioned and therefore considered outside of the scope for this study. For each of the four criteria, a score between 1 and 5 will be given. Each criterion is then multiplied by its assigned weight. Finally, the scores are summed to generate a final (weighted average) score of the concept. The concept with the highest final score will be selected. Below, the four criteria used are discussed further. The weights are given in percentages of the total weight and are set through discussions with KLM. Note that these are still estimations, and as such, the trade-off are still sensitive to changes in these weights. In the matrices, the scores are linked to colours as well, where a score of 1 is red, 2 orange, 3 yellow, 4 light green, and finally, a score of 5 green. In each cell, the colour name is also given, in case of black and white prints or if the reader has colour blindness. Furthermore, the column width is set relative to the weight of the respective criteria.

4.1.1. Net Present Value

To measure the value of a concept, the Net Present Value (NPV) of a concept is calculated. The NPV takes into account the reduction in cost it generates per year as calculated in chapter 3, the initial investment, and the time value of money, for which an annual effective discount rate is used. The time value of money describes how time influences the value of cash flows. For example, 1 euro is worth more to an investor now than in 10 years, as they could invest and multiply that euro within those 10 years. The NPV is calculated through the following equation:

$$\text{NPV} = -I + \sum_{t=1}^{N} \frac{R_t}{(1+i)^t} \tag{4.1}$$

Here I indicates the investment cost (one-time, at year 0), N time horizon in years, R_t the net savings in year t, and i the discount rate. Since the net savings are calculated without inflation, the real discount rate is used, as this also does not use inflation.

For constant savings, the equation can be simplified using a geometric series. With $\frac{1}{1+i}$ as the both the first term and common ratio:

$$\sum_{t=1}^{N} \frac{1}{(1+i)^t} = \frac{\frac{1}{1+i}(1-(\frac{1}{1+i})^N}{1-\frac{1}{1+i}} = \frac{1-(1+i)^{-N}}{i} \tag{4.2}$$

Substituting this into the original equation gives:

$$\text{NPV} = -I + S\frac{1-(1+i)^{-N}}{i} \tag{4.3}$$

A value of 4% is used for the discount rate i, as recommended by EUROCONTROL.[46][47] For the time horizon, a standard value of 15 years is taken. This results in the following equation for NPV with a constant net savings:

$$\text{NPV} = -I + S\frac{1-(1+0.04)^{-15}}{0.04} \simeq -I + 11.12S \tag{4.4}$$

For NPV calculations without constant net savings, the following equation should be used:

$$\text{NPV} = -I + \sum_{t=1}^{15} \frac{R_t}{1.04^t} \tag{4.5}$$

Note that other operational costs or reductions in costs due to, for example, the reduction in staff, are omitted in this calculation. With staff reduction, this of course, creates a cost reduction as well. However, as all systems are considered fully automated, the staff reduction, and thus the reduction in cost, is equal across all concepts. This, therefore, also means that whilst this will create some error in the NPV calculation, it will not affect the comparison between concepts.

As KLM is currently struggling financially, this criterion is extremely important to justify the investment needed. As such, it also receives the largest weight at 40%. The scores are given linearly, with an NPV of €-500’000 or lower receiving a score of 1 and an NPV of €500’000 or higher receiving a score of 5. NPV scores between these are given linearly. For example, an NPV value of €125’000 will receive a score of 3.5.

4.1.2. RAMS

The reliability of the systems is vital, since an unreliable system will cause many delays. Next to reliability, other factors such as maintainability are vital as well. As such, a Reliability, Availability, Maintainability, and Safety (RAMS) criterion is added with a weight of 25%. The components of this can be described as follows [48]:

- Reliability: The ability of a system to perform its function without failure over time, where the failure rate is an important metric
- Availability: The fraction of time the system is operational, taking into account the maintenance schedule. Here, the ratio of uptime to total time (uptime + downtime) is an important metric
- Maintainability: How easy and quickly the system can be maintained or restored to an operational state after a failure occurs. The mean time to repair is the metric used for this.
- Safety: The ability of a system to operate safely without causing harm.

Unfortunately, it is impossible to quantitatively value the concepts of reliability, availability, and maintainability, as many concepts don't yet exist yet and, as such, there is no available data. The concepts will therefore also be graded relatively to each other. The scores are given as follows:

1. Very unreliable or unsafe, very prone to failures and will require human intervention very often
2. Unreliable or unsafe, failures will occur often that requiring human intervention
3. Somewhat reliable and safe, anomalies occur sometimes, and require human intervention
4. Reliable and safe, anomalies occur sometimes, but can also sometimes be solved remotely
5. Very reliable and safe system, barely any anomalies occur. Anomalies can be solved remotely

Note that this is a guideline. For example, a system can be graded lower due to the abnormally high impact of failures or be graded higher due to the ease of solving common failures. See Appendix B for further justifications of values.

4.1.3. Flexibility

With different aircraft types come different requirements. As such, certain concepts might only be able to service one aircraft type due to their fixed location, whilst other concepts can service any aircraft. Due to the impact this has, this criterion has a weight of 20%. The scores are given as follows:

1. Concept can only service one aircraft type
2. Concept can only service very similar aircraft types with minor deviations.
3. Concept can only service similar aircraft types with similar dimensions.
4. Concept can either service all narrow-body or wide-body aircraft
5. Fully flexible, concept can service any aircraft

4.1.4. Technological Readiness Level

With different technological readiness levels come different development times for the concepts. A good concept might be worse if it takes a lot more development than a concept that can be implemented very quickly. That said, due to the long-term nature of automating turnarounds, this criterion has the lowest weight at 15%. The TRL also has a significant effect on the reliability of the concept, which is an important metric next to the performance of said concept. For this study, the TRL levels set by the European Union are used.[49] The scores are given as follows:

1. TRL of 3 or lower
2. TRL of 4
3. TRL of 5 or 6
4. TRL of 7
5. TRL of 8 or 9

4.2. Generic Requirements

Before any concepts can be generated, some generic requirements need to be set. It is vital that all concepts, regardless of operation, adhere to these requirements, as seen in Table 4.1.

Table 4.1: List of general system requirements

ID	Description	Rationale
Gen-01	The system shall not permanently block aircraft parking or pushback, nor any other ground operations.	Whilst the system can be, for example, integrated in the ground, it should of course not hinder any other operations and be in a fully retracted state when not operating.
Gen-02	During nominal operations, the system shall be able to operate without manual interventions.	The system should be fully automated, but manual interventions are acceptable when anomalies occur.
Gen-03	The system shall be able to operate during normal operational conditions, including rain, snow, nighttime, freezing temperatures and low visibility.	It is vital that the system is able to operate during less than ideal conditions, especially since some airports, such as Schiphol Airport, experience them very frequently.
Gen-04	For fixed systems, a manual override shall be present, allowing the manual execution of the operation and the reverting of the system to its original state.	To mitigate the impact of any anomalies, a manual override should be present to make sure the operation can be performed manually during a system malfunction.
Gen-05	The system shall communicate its status, including any anomalies, to the ground personnel.	Communicating the status of the system is vital not only for the operations, but also for safety. If any anomalies occur, it is of course also very important to communicate this, such that it can be resolved or mitigated.
Gen-06	The system shall be as safe or safer than the current method used to perform the operation for both personnel and passengers.	The safety for both personnel and passengers is, of course, vital, and compromising on this to automate the operation is not acceptable.
Gen-07	The system shall be capable of zero-emission operation.	Environmentally friendly operations are important to improve the working conditions of ground personnel, even if the amount of ground personnel is reduced significantly. Moreover, non-zero-emission operations might be restricted in the future as well.

4.3. Wheel Chock Placement

Automating the wheel chock placement can help reduce the turnaround time of an aircraft since the rear chocks can then be placed without having to wait for the engines to be fully stationary. Several possible solutions are explored, most of which are derived from automated truck chock systems. In Table 4.2, the requirements specific to wheel chock placement can be found.

Table 4.2: List of system requirements for wheel chock placement

ID	Description	Rationale
Chocks-01	The system shall be able to place and remove wheel chocks in front and behind the front gear and either the left main landing gear or right main landing gear during normal wind conditions.[27]	This is the main functionality of the wheel chock system.
Chocks-02	For the nose landing gear, the system shall be able to place chocks at a distance of approximately 0.05m from the tyre.[27]	Since the aircraft can still shift a bit after parking, a small gap should be left from the nose gear to prevent any damage and to prevent the chocks from getting stuck after a shift occurs, hindering their removal.
Chocks-03	For wind speeds exceeding 35 knots (64km/h) and/or when apron slopes and/or conditions require such, the system shall be able to place and remove additional wheel chocks or allow the manual placement of extra chocks. For this, a wheel chock shall be placed (either automatically or manually) in front of and behind each tyre.[27]	During heavy winds, the forces on the aircraft are larger as well, warranting the use of more chocks. Due to the low frequency of occurrence, allowing for manual placement is acceptable.
Chocks-04	The system shall support, though not necessarily simultaneously, chock placement for multiple aircraft types, including narrow-body and wide-body jets.	Both narrow-body and wide-body jets need to be serviced. A choice can be made to have the system only service a subset of aircraft types on a ramp, as long as it is possible to make this choice for all aircraft types.
Chocks-05	The system shall communicate its status to the aircraft pilots.	Communicating the status of the wheel chock placement system is required, since the aircraft pilots need to be aware when they can release the parking brake.

4.3.1. Concept 1: Integrated chocks

One solution used sometimes within the trucking industry is to attach an extendable chock to the bottom of the truck, see Figure 4.1. That way, the truck driver only needs to press a button to place the chocks, making it extremely fast. However, due to the added weight that this would add to an aircraft, it would also be extremely expensive. Moreover, adding parts to an aircraft would require significant regulatory changes and verification, increasing the cost even further.

Figure 4.1: Integrated chock system from AutoChock[1]

4.3.2. Concept 2: Pushback trucks

In the future, tractors such as Taxibot could be used to taxi from and to the runway.[14] Instead of removing the tractor after parking the aircraft, the tractor could also remain attached and serve as a replacement for the wheel chocks. Whilst this would simplify and speed up the turnaround operations, it would require a significant increase in tractor count, and as a result, it would be a very expensive method. Additionally, regulations would need to be adjusted to omit having to place wheel chocks on the main landing gear.

4.3.3. Concept 3: Rotating chocks

Next to attaching an automatic chock system to the aircraft or pushback truck, it can also be integrated into the ramp. One possibility for this is the use of rotating chocks, such as the Calematic system as seen in Figure 4.2. This system consists of metal blocks that can rotate upwards against the wheel. A large downside of this system is that the location of the system needs to be different for different aircraft. A 737-800, for example, has a track width of 5.7m, whilst a 777-300 has a track width of 10.97m. This would result in the need for multiple systems in one ramp or further restriction of aircraft type for each ramp. Moreover, the construction of this system requires the ramp to be closed, increasing the financial cost. The design of the rotating chocks would also need to be strengthened from the ones used in the trucking industry due to the higher tyre pressures used in aircraft tyres and larger weights per wheel.

Figure 4.2: Calematic chocks[2]

Figure 4.3: Rail chocks[3]

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[1] https://www.autochock.com/

[2] norsud.com

[3] kelleydocksolutions.com

4.3.4. Concept 4: Rail chocks

Similar to the Calematic system, a rail system can be used. In this system, a chock can move along rails and be positioned near or against the wheel, see Figure 4.3. It should be noted, however, that a chock needs to be placed both in front and behind the wheel, requiring two rail chocks. The chocks must also rotate and move into the ground to allow the aircraft to park. The rail chock system also suffers from the same problems as the Calematic chocks for track width and ramp closure during construction. That said, it does give more flexibility to the longitudinal positioning of the chocks.

4.3.5. Concept 5: Chocks robot

A separate automated vehicle can also be created to place the chocks. The main advantage of such a robot is that it does not require any construction on the ramp and can service any aircraft. An obvious downside is that such a robot requires a lot of development to drive (semi-)autonomously, without causing collisions or getting in the way of other operations. Breugelmans did a master's thesis on such a robot, and designed a prototype to pick up and place the wheel chocks, which can be seen in Figure 4.4.[50] Whilst it could not pick up real chocks due to their weight, it demonstrated basic functionalities and a clear road to full implementation. To reduce developmental costs, the vehicle can also be remotely controlled by the personnel originally placing the chocks. This would allow them to place the chocks immediately after the aircraft has parked, without having to develop a self-driving system. Another downside of such a vehicle is that each chock would have to be placed individually, and cannot approach the aircraft whilst the engines are running, making it significantly slower than the solutions discussed previously. It will also have a lower reliability due to the possibility of navigational or deployment errors.

Figure 4.4: Chock Robot prototype [50]

4.3.6. Trade-off Analysis

Below in Table 4.3, the trade-off table of the different solutions can be found. The justifications for all scores can be found in section B.1.

Table 4.3: Trade-off analysis wheel chock placement

	Net Present Value [40%]	**RAMS [25%]**	**Flexibility [20%]**	**TRL [15%]**	**Weighted Average**
Integrated Chocks	Red 1	Light Green 4	Red 1	Orange 2	Orange 1.90
Pushback Trucks	Orange 1.53	Light Green 4	Light Green 4	Yellow 3	Yellow 2.86
Rotating Chocks	Yellow 3.47	Light Green 4	Yellow 3	Yellow 3	Yellow 3.44
Rail Chocks	Yellow 3.13	Light Green 4	Yellow 3	Yellow 3	Yellow 3.30
Chocks Robot	Yellow 3.05	Orange 2	Green 5	Red 1	Yellow 2.87

As expected, the use of integrated chocks is not viable. The rotating chocks and rail chocks have high performance and reliability, but have low flexibility. Within this preliminary analysis, it is hard to say which of these two options would perform better. If the budget available is small, chock robots can be used as well, though they lack the speed and technological readiness of the rotating and rail chocks. As the rotating chocks system has the highest score, it is chosen as the single-operation solution.

4.3.7. Sensitivity Analysis

From the trade-off, it is clear that the rail chocks concept has a weighted average near the weighted average of the chosen concept of rotating chocks, warranting a sensitivity analysis into it. Whilst the weighted average of the chocks robot concept is significantly lower, a sensitivity analysis should be done for this concept as well, due to the large differences in score compared to the chosen concept. The integrated chocks and pushback trucks concepts are deemed insensitive, due to their very low score in NPV. Again, an adjustable Excel file with the trade-off can be found on GitHub

Rail Chocks

For the Rail chocks, the trade-off is not sensitive at all to the weights of the criteria, since, except for the Net Present Value, all scores are the same. This is also to be expected with the similarity the two concepts have. For the Net Present Value, the main difference comes from the difference in savings generated, which comes from a difference in operational time. For this, the rotating chocks are assumed to have an operational duration of 5.5 seconds, whilst the rail chocks concept has one of 10 seconds. Whilst the exact number can vary, the rail chocks can be safely assumed to always be slower due to the added distance the chock needs to travel. A difference in RAMS or TRL score is possible with further research, but with the high similarity, this is not expected. As such, this trade-off is deemed insensitive.

Chocks Robot

For the chocks robot concept to have the highest weighted average score, the flexibility weight would need to increase significantly, and RAMS and TRL weights would need to decrease. For example, a weight distribution of 40.00% 15.00% 35.00% 10.00% for NPV, RAMS, Flexibility and TRL, respectively, would result in the chocks robot being picked. That said, an RMS and TRL weight this low is fairly unrealistic, due to the importance of creating a reliable system. The chocks robot concept is therefore only viable for ramps where flexibility is of utmost importance, and if the RAMS score of the chocks robot can be increased.

4.4. GPU Connection

To reduce the amount of time required, personnel needed, and the staff workloads, the connection can be made automatically. Below, two options are discussed, which could be implemented for certain methods used today. In Table 4.4, the requirements specific to GPU connecting can be found.

Table 4.4: List of system requirements for GPU connection

ID	Description	Rationale
GPU-01	The system shall be able to plug in the GPU cable, and when required remove it again.	This is the main functionality of the GPU connection system.
GPU-02	The system shall be able to open the external power receptacle on the aircraft, and after removing the cable, close it back up.	Before the cable can be plugged in, the small door must be opened by pressing the 3 buttons on the door. After removing the GPU cable, the door should of course be closed again.
GPU-03	The system shall not activate automatically before the aircraft is fully stationary and nose gear wheel chocks are placed.	Activation before the nose gear wheel chocks are placed can be quite dangerous if the aircraft starts moving again whilst the GPU cable is connected.
GPU-04	The system shall support, though not necessarily simultaneously, chock placement for multiple aircraft types, including narrow-body and wide-body jets.	Both narrow-body and wide-body jets need to be serviced. A choice can be made to have the system only service a subset of aircraft types on a ramp, as long as it is possible to make this choice for all aircraft types.

4.4.1. Concept 1: Pit system with robotic arm

For both the jet bridge-mounted GPU and the ground power pit, the only manual labour needed is connecting the cable to the aircraft, as the cable is already very close to the aircraft attachment point. This can be automated by utilising a robotic arm that holds the cable and automatically secures the cable to the aircraft. Such a robotic arm would, unfortunately, however, be very expensive, due to the high weight of the cable and the slightly different attachment points for different aircraft.

4.4.2. Concept 2: GPU AGV

In warehouses, Automated Guided Vehicles (AGVs) are becoming more common each year. The mobile GPU could be similarly converted to a self-driving AGV. This would eliminate the need to manually transport the GPU to the aircraft, which especially saves time when remote ramps are used. It could also contain a robotic arm to connect to the aircraft automatically. To reduce emissions, the E-GPUs could be used again, with the battery now also powering the electric motors needed to drive. Whilst an AGV system would be more expensive, it gives more flexibility and can service multiple stands, thus requiring fewer units, making it a cheaper solution. As with other operations, using AGVs does increase the chance of accidents and failures. Since the AGV will first need to move into position, it will also be slightly slower than the pit system.

4.4.3. Trade-off Analysis

Below in Table 4.5, the trade-off table of the different solutions can be found. The justifications for all scores can be found in section B.2.

Table 4.5: Trade-off analysis GPU connection

	Net Present Value [40%]	RAMS [25%]	Flexibility [20%]	TRL [15%]	Weighted Average
Pit System	Orange 2.2	Light Green 4	Yellow 3	Red 1	Yellow 2.63
AGV	Yellow 2.88	Yellow 3	Green 5	Red 1	Yellow 3.05

It is clear that both options have their ups and downsides. From the table, it can be determined that the AGV concept has the highest score due to a higher NPV and flexibility. Whilst a stand with little variety in aircraft types might be better suited for the pit system, the lower NPV value still makes the AGV unit more attractive, which is mostly caused by its ability to service multiple ramps.

4.4.4. Sensitivity Analysis

In this trade-off, the pit system has a significantly lower score in both NPV and flexibility, whilst it has a slightly higher score in RAMS. For the pit system to score higher than the AGV system on average, the weight of both NPV and flexibility would need to drastically decrease, whilst the score of flexibility or NPV would need to increase. As drastic changes would be needed, this trade-off is deemed insensitive. Again, an adjustable Excel file with the trade-off can be found on GitHub

4.5. PCA Connection

For preconditioned air, the same automated solutions applied to the GPU connection can be used. A robotic arm can be used for the jet bridge-mounted unit and the pit to automatically connect the PCA tubes. The mobile PCA unit could again be turned into an (electric) AGV. As the technologies and concepts are extremely similar, the trade-off used for the GPU connection can be used again, yielding the same result as in Table 4.5. The justifications used in section B.2 can be used again as well.

4.6. Cone Placement

With the large distances that can be travelled faster, simultaneously with multiple systems, or skipped completely through a different solution, this operation can be sped up significantly through automation. As other operations using vehicles are dependent on the cones being placed, this can speed up the total turnaround time as well. In Table 4.6, the requirements specific to cone placement can be found.

Table 4.6: List of system requirements for cone placement

ID	Description	Rationale
Cones-01	The system shall be able to place safety cones a maximum of 1 meter outward from each wing tip and a maximum 1 meter in front of each engine.[27]	This is the main functionality of the cone placement system.
Cones-02	For wide-body aircraft, the system shall place and remove cones 1 meter outward of both engines, instead of the two cones placed near the wing tips.	For wide-body aircraft, the wing tip cones can be placed next to the engines due to the larger wing clearance.

Cones-03	The system shall not activate before the aircraft engines are stationary and the anti-collision lights are turned off.	Placing cones in front of the engine whilst they are running is very dangerous, as the engines can easily suck in a cone or small robot, causing massive damage and possibly creating dangerous situations for crew and passengers.

4.6.1. Concept 1: AGV with placing mechanism

During highway maintenance, cones are often placed and picked up automatically using a mechanism attached to a truck. Such a mechanism could be adjusted for use on an aircraft stand. One example of this is the use of a robotic arm with a magnet designed by Wenlong et al.[51], as seen in Figure 4.5. Such a vehicle could also be made smaller due to the few cones needed and by removing the driver, turning it into an AGV. Whilst such a system would be relatively cheap, multiple units or a self-driving vehicle would need to be used to see any performance improvement. Furthermore, such a system might struggle to pick up cones that have been knocked over.

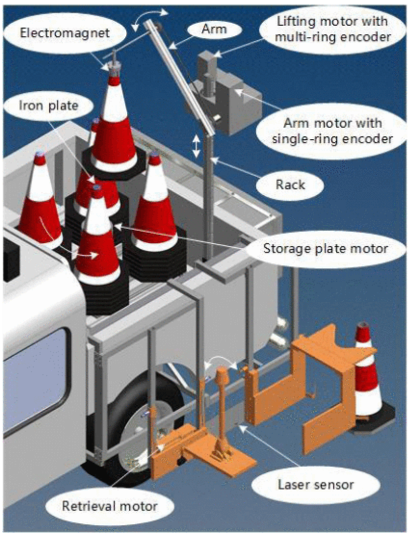

Figure 4.5: Cone placer with robotic arm and magnets[51]

4.6.2. Concept 2: In-ground

To decrease the time needed, an in-ground cone system can be used as well. Here, a cone or bollard would flip or be lifted into place. This, of course, does require the positions of the cones, and thus the aircraft type not to change. Furthermore, the aircraft parking must be quite precise to ensure that the cones are in the right location. Whilst this would be a very expensive method, an in-ground cone system would be extremely fast, with all cones being deployed nearly instantaneously.

4.6.3. Concept 3: Mobile cones

The cones placed can also be turned into tiny AGVs that drive into place by themselves. Since no vehicles are allowed to drive on the ramp when the cones are not placed, the self-driving cones do not need advanced collision avoidance methods either. The cones could simply follow a preprogrammed path and destination based on the aircraft type present. Several tests with driving cones have been performed already, for example, by Transurban in an attempt to make highway maintenance safer.[52] Whilst these could drive simultaneously, reducing the duration of the operation, they would need to wait for the engines to be fully stationary due to their tiny weight. This also makes them unreliable, since they can easily tip over during windy conditions.

4.6.4. Concept 4: Substitute with virtual walls

Since cones are only present for visual guidance for humans, safety cones are not needed when no manually driven vehicles are present. In such a fully automated ground operation, the cones can be replaced by a virtual, digital no-go zone, where the AGVs are told to keep out of. This would thus result in the complete elimination of this operation, improving efficiency significantly. For such a virtual zone to be implemented, however, regulations must be changed to allow operations to be performed without safety cones.

4.6.5. Trade-off Analysis

Below in Table 4.7, the trade-off table of the different solutions can be found. The justifications for all scores can be found in section B.3.

Table 4.7: Trade-off analysis cone placement

	Net Present Value [40%]	**RAMS [25%]**	**Flexibility [20%]**	**TRL [15%]**	**Weighted Average**
AGV System	Orange 2.42	Yellow 3	Green 5	Orange 2	Yellow 3.02
In-ground	Yellow 2.94	Light Green 4	Red 1	Yellow 3	Yellow 2.83
Mobile cones	Yellow 2.84	Red 1	Green 5	Yellow 3	Yellow 2.84
Virtual walls	Green 4.86	Green 5	Green 5	Green 5	Green 4.94

The use of virtual walls is obviously the most efficient, but can unfortunately only be implemented when all vehicles are turned into AGVs or other automated systems. For the other concepts, they clearly each lack in a specific criterion, with an AGV system being too expensive for its lack of performance improvement, the in-ground solution not being flexible, and the mobile cones being unreliable. This also means that it is hard to determine which would perform best in general, as each performs best in certain scenarios. For example, the in-ground solution would work best on a ramp with little aircraft type variation, such as the southern B-pier gates at Schiphol, which only service smaller cityhopper aircraft.

4.6.6. Sensitivity Analysis

With its incredibly high score, the virtual walls concept will always come on top, and is impervious to changed weights or increased scores for the other concepts. When a hybrid solution is required, and the virtual wall system is therefore not an option, the trade-off is very sensitive to changes in weights or scores. For example, a score increase from 1 to 2 for flexibility for the in-ground solution or a similar increase in the RAMS score for the mobile cones concept would result in them getting a higher weighted average than the AGV system. To determine which of these three concepts would be best in case a hybrid solution is required, more research would be required. Again, an adjustable Excel file with the trade-off can be found on GitHub

4.7. Technical Inspection

The inspection done by the technicians can be automated by using cameras and other sensors on mobile or fixed platforms, and computer vision. For this analysis, the automated concepts will be split up into land-based, air-based (flying), and fixed platforms. For the sensors, various types of cameras can be used, including normal visual, infrared (IR), ultraviolet (UV), and point-cloud cameras. It should be noted that automating this operation would require significant changes in regulations, independent of the method used. In Table 4.8, the requirements specific to technical inspection can be found.

Table 4.8: List of system requirements for technical inspection

ID	Description	Rationale
Insp-01	The system shall be able to check the entire underside, engines and sides of the aircraft for any damage or abnormalities.	This is the main functionality of the wheel chock system.
Insp-02	If any abnormalities are detected, ground personnel and pilots shall be informed of the type, severity, and location of the abnormality.	If any damage is detected, this should be communicated with both ground staff and pilots to make sure the aircraft does not depart with severe damage.
Insp-03	The system shall support, though not necessarily simultaneously, chock placement for multiple aircraft types, including narrow-body and wide-body jets.	Both narrow-body and wide-body jets need to be serviced. A choice can be made to have the system only service a subset of aircraft types on a ramp, as long as it is possible to make this choice for all aircraft types.

4.7.1. Concept 1: Land-based robot

Land-based platform robots, such as the ones from Invert Robotics[53], are well developed and used in several industries already. Another good example of this is Boston Dynamics' Spot, a dog-like robotic platform able to traverse multiple types of terrain whilst carrying up to 14 kg of payload and used in several industries to perform inspections, see also Figure 4.6.[54] Such a robot has a maximum speed of around 1.6 m/s and a battery life of around 90 minutes, making it a viable option for automated inspection. The biggest challenge in using such a robot is its interaction with other vehicles, as avoiding collisions with these vehicles and the aircraft is, of course, vital.

Figure 4.6: Boston Dynamics' Spot[4]

4.7.2. Concept 2: Inspection drones

Drones can also be used for visual inspections. Whilst they come with extra complications such as advanced collision avoidance, regulation changes and unstable sensors, they also give extra benefits. For example, the use of drones allows the topside of an aircraft to be inspected as well, improving safety. Moreover, drones can move a lot faster, and as such, fewer are needed than land-based platforms to service all stands. Several companies are already working on air-based visual inspections, some examples are: Donecle (France)[55], Mainblades (Netherlands)[56], Luftronix (US)[57], Autaza (Brazil)[58], Parrot (USA)[59], and DJI (Netherlands)[60]. Whilst the drones can perform an inspection very quickly, they might not be able to fly during poor weather conditions, severely impacting the reliability of the system.

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[4] https://bostondynamics.com/news/boston-dynamics-expands-global-sales-of-spot-robot/

4.7.3. Concept 3: Fixed cameras

Whilst a mobile platform allows the cameras to get close to the aircraft, it also comes with several problems, such as interaction with other vehicles, collision avoidance with the aircraft, recharging, and delays due to pathing errors. Mounting several PTZ (pan-tilt-zoom) cameras on multiple strategic positions can image most of the aircraft, imaging and inspecting the aircraft almost instantly. Whilst this would require expensive new infrastructure at every stand, several studies have researched this method successfully.[61][62] That said, some areas, like the inside of the engines, are impossible to image from the outside edge of the stand. To inspect these areas, a camera would have to be mounted in the ground of the stand to get the required angle. This would, of course, come with significant infrastructural costs and reduced flexibility. Another option would be to only partially use fixed cameras and perform the inspection on blind spots manually or via mobile platforms discussed earlier.

4.7.4. Trade-off Analysis

Below in Table 4.9, the trade-off table of the different solutions can be found. The justifications for all scores can be found in section B.4.

Table 4.9: Trade-off analysis technical inspection

	Net Present Value [40%]	**RAMS [25%]**	**Flexibility [20%]**	**TRL [15%]**	**Weighted Average**
Land-based	Yellow 2.80	Light Green 4	Green 5	Yellow 3	Light Green 3.57
Drones	Green 5.00	Red 1	Green 5	Green 5	Light Green 4.00
Fixed cameras	Green 5.00	Light Green 4	Light Green 4	Light Green 4	Light Green 4.40

As can be seen, the air-based system's low RAMS due to its inability to function in poor weather conditions severely impacts its performance. In fact, its reliability and regulatory challenges due to being airborne might make the concept be deemed completely infeasible, also due to its possible inability to adhere to requirement Gen-03. Whilst the fixed cameras can become very expensive due to the extra cameras needed to cover blind spots, the NPV is still very high at more than €800'000 due to its incredible speed. In combination with its high RAMS makes this is the better option, even if it has the same score as the drones concept.

4.7.5. Sensitivity Analysis

With its significantly lower score, the trade-off between the land-based and fixed cameras concepts is insensitive. For the drones concept, a solution would need to be found to allow the drones to operate in less-than-ideal weather conditions to increase their RAMS score. Only if this can be done will the drone concept receive a higher weighted-average score. Reducing the RAMS criterion weight below 15% to achieve a higher weighted average score is deemed unrealistic given the importance of reliability. Again, an adjustable Excel file with the trade-off can be found on GitHub

4.8. FOD Check

Automating FOD checks can reduce workload, but also increase the accuracy of detection and thus safety. A variety of systems can be used to check for FOD automatically, which are discussed below. The main challenge in automated detection comes from the variety of debris types, with different sizes and materials for each type. Next to this, different debris types will have different hazard levels, with some requiring immediate removal, whilst others do not. In Table 4.8, the requirements specific to technical inspection can be found.

Table 4.10: List of system requirements for FOD check

ID	Description	Rationale
FOD-01	The system shall fully scan a ramp and identify and classify the FOD present on the ramp.	This is the main functionality of the wheel chock system.
FOD-02	After identifying the FOD, the system shall be able to pick up and remove the FOD from the ramp.	Since FOD is fairly common, manual removal of any detected FOD would require significant efforts from staff, reducing the effectiveness of automation.
FOD-03	If any FOD is classified as dangerous, either to the system or an aircraft it originates from, the system shall inform a controller of the FOD, its classification, and location.	Sometimes, FOD is an important sign that something is wrong with an aircraft. As such, this mustn't be lost by the automated identification and removal of FOD.
FOD-04	The system shall be able to perform FOD checks for all ramp types and sizes present at Schiphol Airport.	Ramps have different sizes depending on what aircraft types they service. It is important that the system can also service the larger ramps present. To somewhat limit the number of ramp types, the ramps at Schiphol Airport are taken.

4.8.1. Mobile vs Fixed

Whilst fixed solutions are very useful for runways and taxiways, they are less so for aircraft stands, since these do not need live detection. Only before an aircraft arrives is an FOD check necessary. To combat this, mobile platforms can be used as well, on which radar, optical, LiDAR, or multiple sensors can be attached. This significantly reduces the number of sensors needed, and thus the financial cost. For example, if a mobile platform takes a couple of minutes to check a ramp, it could easily service 5 nearby stands at the same time. Mobile platforms could be modified to be able to pick up FOD as well, making sure that no manual removal is needed. An example of this is the robot in development by Roboxi.[63] For this study, the use of such a mobile platform is assumed, as this pickup is deemed to be required to be automated (FOD-02). Whilst it is possible to have fixed sensors and use robots to purely remove debris, and therefore reduce the amount of robots required, this is less cost efficient as these robots will also need to have sensors to be able to detect the FOD which was assigned for removal. In the following subsections, a trade-off will be made between the different sensors that can be used to detect and identify FOD.

4.8.2. Concept 1: Radar

To detect FOD, one of the simplest ways is through millimetre-wave radar. Radar gives high resolution and high detection accuracy, whilst being unaffected by weather conditions. The main downside of radar is that it cannot give a clear (colour) visual of the object, which makes it harder to identify and thus remove the target.[21] Radar is already used extensively for FOD detection on runways, and examples of such a radar system are Trex Enterprises' FOD Finder[20] and QinetiQ's Tarsier system as seen in Figure 4.7.

4.8.3. Concept 2: Optical

Next to radar, FOD detection through image and video processing is also possible. Whilst this does provide an intuitive image for removal and the ability to classify the hazard level, optical methods suffer from poor performance during bad weather, at night, and when the object is of similar colour to the ground. Recent developments in AI, however, show great potential in allowing optical detection to perform well.[19] Some companies, such as Roboxi,[63] are currently in the process of prototyping FOD detection systems through optical imaging.

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[4] flickr.com/photos/35264437@N06/3766309117/in/album-72157621752216399

4.8.4. Concept 3: LiDAR

Similar to self-driving cars, LiDAR can be used instead of radar. Although less developed than radar, several promising tests have been performed with LiDAR FOD detection. Here, tests used either top-down LiDAR,[16][17] or a rover that sent a laser across the tarmac, as seen in Figure 4.8.[18] That said, the tests mentioned struggled with detecting small objects such as socket wrenches, and thus needed a system running along the entire length of the area covered to get high performance. Similar to radar, LiDAR cannot give a clear visual of the object to identify its hazard level.

Figure 4.7: QinetiQ's Tarsier system[5]

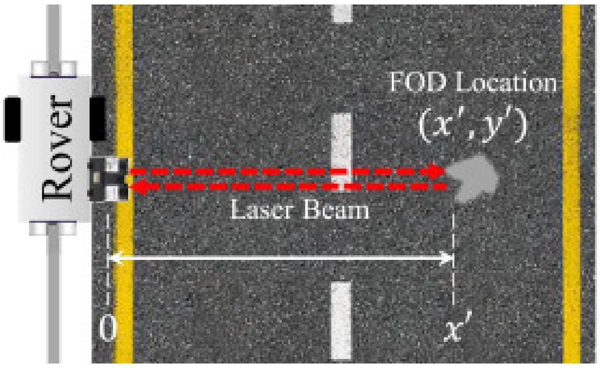

Figure 4.8: FOD LiDAR Rover[18]

4.8.5. Concept 4: Hybrids

To improve accuracy and have the benefit of both the optical and radar methods, some companies have developed a hybrid of both optical and radar systems. Xsight systems developed FODetect® (Figure 4.9), which uses radar and infrared cameras to detect ”objects of various shapes, sizes, and materials on runway surfaces and perform satisfactorily in nighttime, daytime, sun, rain, mist, fog, and snow conditions, as required by FAA Advisory Circular 150/5220-24: ’Airport Foreign Object Debris (FOD) Detection Equipment’”.[15] Whilst a hybrid system has high accuracy and the usage of multiple sensors minimises false positives, it also increases the financial cost and complexity of the system. With multiple sensor types, however, dual modular redundancy can be used as well: it can determine if one of the sensors is giving a false positive or negative when they do not agree, giving extra reliability. Whilst it will not be able to determine which sensor is wrong, as with triple modular redundancy, it can decide to take a closer look. If this fails as well, it can also be programmed to send a signal to a human operator to determine if it is FOD or not.

Figure 4.9: FODetect® system[6]

4.8.6. Trade-off Analysis

In Table 4.11, the trade-off table of the different solutions can be found. It should be noted that in this case, the criteria are changed to better suit the trade-off. The flexibility criterion is removed since the FOD check happens before aircraft arrive, and the NPV since there is no financial benefit from reducing the operational time. It should

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[6] ainonline.com/aviation-news/air-transport/2024-04-25/sensors-and-ai-combine-deal-foreign-object-debris

be noted that there is a significant economic benefit when FOD checks are improved, as this reduces the costs associated with FOD-related damage and delays. The following criteria are used for this system:

- Cost 15%: The initial cost of the system, scored relatively to each other, with a score of 5 being given to the cheapest system. A small weight is given to this criterion, as the cost of the sensors relative to the mobile platform is fairly small, and therefore does not influence the final cost a lot.
- Detection 40%: The ability of the system to correctly detect FOD. Scored relatively to each other, with a score of 5 given to the best performing system. As this is the most important function of the sensors, this criterion is also given the highest weight.
- Identification 30%: The ability of the system to correctly identify and classify the detected FOD. The best system is given a score of 5, and others are scored relatively to that. A weight of 30% is given to indicate the significance of correctly identifying debris and its hazard level.
- TRL 15%: The technological readiness level is scored and graded in the same manner as discussed earlier.

The justifications of all values can be found in section B.5.

Table 4.11: Trade-off analysis FOD check

	Cost [15%]	**Detection [40%]**	**Identification [30%]**	**TRL [15%]**	**Weighted Average**
Radar	Light Green 4	Light Green 4	Orange 2	Green 5	Light Green 3.55
Optical	Green 5	Orange 2	Green 5	Yellow 3	Light Green 3.50
LiDAR	Orange 2	Yellow 3	LightGreen 4	Orange 2	Yellow 3.3
Hybrid	Orange 2	Green 5	Green 5	Green 5	Green 4.55

From the table, it is clear that LiDAR is the least feasible, whilst Radar and Optical both have their ups and downsides, mainly in detection and identification. When detection is deemed more important, Radar is preferable, whilst Optical is preferable when debris identification is more important. When more financial budget is available, a hybrid solution can be chosen, which has the benefits of both. Since the cost of the sensors is small compared to the cost of the mobile platform, it can be concluded that the use of a hybrid is most preferable, which is also very clear from the weighted average. As such, this is also the chosen concept for a single-operation solution.

4.8.7. Sensitivity Analysis

As the hybrid concept has a far higher weighted average score than the other concepts, this trade-off is insensitive to changes to the weights or scores. For the radar concept to come out on top, the weight of cost would need to be nearly tripled, whilst the identification weight is halved. This is unrealistic due to the relatively low cost of these sensors to the mobile platform and the importance of identifying hazardous FOD. Again, an adjustable Excel file with the trade-off can be found on GitHub

4.9. Multi-Operation systems

In certain cases, a single system can be used to automate multiple operations. In each of the previously mentioned operations, the use of an AGV was discussed. Instead of having an AGV specialised for each task, a multitasking AGV that could, for example, both inspect the aircraft and connect the GPU can be used. Examining the trade-off tables, the AGV system was deemed feasible for all operations, although it was considered non-ideal for wheel chock placement and technical inspection. With this, any combination of these operations can be automated using a multi-operation AGV. For example, combining FOD detection with technical inspection or GPU connection with preconditioned air connection is interesting, since they use similar equipment. This would reduce cost, whilst also reducing the amount of traffic on the stand, and with it, the chances of incidents. In this section, these and other options will be explored.

4.9.1. Combination development

To ease the development of good combinations of operations, the technological commonalities can be analysed between different concepts. For example, the GPU AGV and PCA AGV both have a robotic arm and grabber, whilst the rotating chocks and GPU pit both require ramp closure and underground infrastructure. In Table 4.12, an overview of this can be found. The following commonalities are considered:

- AGV Chassis: A basic AGV chassis, including the drive, battery, and other systems required to move around.
- Navigation system: A navigation system that can keep track of the location of the vehicle, plot a route, and detect and avoid obstacles.
- Machine vision: A system that allows the capability to detect and identify objects using machine vision.
- Robotic arm: A robotic arm with multiple degrees of freedom able to manipulate objects.
- Pick-up system: A system able to pick up objects from the ground. Note that this might be done by the robotic arm mentioned earlier or a separate system that, for example, scoops up objects.
- Storage system: A storage system able to store and deploy objects.
- Ramp closure: Whilst not a technological system, if two systems both require a ramp closure, combining these can simplify the construction and therefore costs.

Table 4.12: Technological commonalities between single operation concepts

Operation	Method	AGV Chassis	Navigatic	Machine Vision	Robotic Arm	Pick-up System	Storage System	Ramp Closure
Wheel Chock	Integrated Ch.							
Wheel Chock	Pushb. Trucks		X					
Wheel Chock	Rotating Ch.							X
Wheel Chock	Rail Chocks							X
Wheel Chock	Chocks Robot	X	X	X		X		
GPU	Pit			X	X			X
GPU	AGV	X	X	X	X	X		
PCA	Pit			X	X			X
PCA	AGV	X	X	X	X	X		
Cones	Pit							X
Cones	AGV	X	X	X		X	X	
Cones	Mobile Cones		X					
Cones	Virtual walls							
Tech. Inspection	Land-Based	X	X	X				
Tech. Inspection	Drones		X	X				
Tech. Inspection	Fixed Cameras			X				X
FOD Check	AGV	X	X	X		X	X	

Table 4.13: Scoring for combinations between single-operation concepts

Operation		FOD Check	FOD Check	Chocks	Chocks	GPU	GPU	PCA	PCA	Cones	Cones	Cones	Tech. Insp.	Tech. Insp.	Tech. Insp.
	Solution	AGV	Fixed	Fixed	AGV	Pit	AGV	Pit	AGV	Pit	AGV	Mobile	AGV	Drones	Fixed
FOD Check	AGV			1	4	1	4	1	4	1	4	1	5	1	1
FOD Check	Fixed			2	1	2	1	2	1	2	1	2	1	1	3
Chocks	Fixed	1	2			3	1	3	1	3	1	2	1	1	2
Chocks	AGV	4	1			2	4	2	4	1	3	1	3	1	1
GPU	Pit	1	2	3	2			3	3	2	1	2	1	1	2
GPU	AGV	4	1	1	4			1	5	1	3	1	3	1	1
PCA	Pit	1	2	3	2	3	1			2	1	2	1	1	2
PCA	AGV	4	1	1	4	3	5			1	3	1	3	1	1
Cones	Pit	1	2	3	1	2	1	2	1				1	1	3
Cones	AGV	4	1	1	3	1	3	1	3				3	1	1
Cones	Mobile	1	2	2	1	2	1	2	1				1	1	2
Tech. Insp.	AGV	5	1	1	3	1	3	1	3	1	3	1			
Tech. Insp.	Drones	1	1	1	1	1	1	1	1	1	1	1			
Tech. Insp.	Fixed	1	3	2	1	2	1	2	1	3	1	2			

Clearly, the AGV systems have major commonalities, which is to be expected. From these commonalities, and also taking into account other factors such as location, size, and operational timing, a score from 1 to 5 can be assigned for each combination. The result of this can be found in Table 4.13. A visualisation of this table can be found in Figure 4.10, where scores of 1 are left out for clarity.

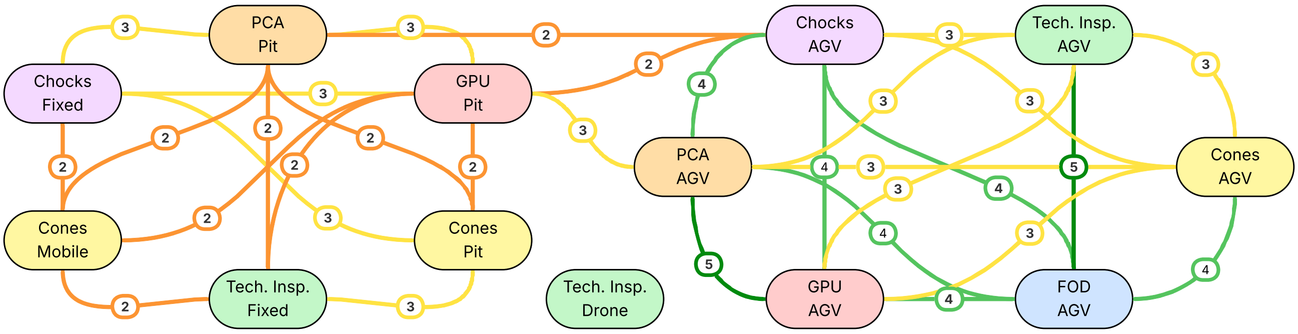

Figure 4.10: Visualisation of Table 4.13. Scores of 1 are left out.

As more than fifty combinations exist, only the combinations with the most clear potential (based on scores) will be analysed for this study. Two obvious combinations are the FOD AGV with the technical inspection AGV and the GPU AGV with the PCA AGV, as these are the only combinations with a score of 5. Next to dual-operation systems, larger combinations can be analysed as well. For this study, a combination of GPU, PCA, Chocks and FOD AGV will be explored, as well as a combination of all systems. For each combination, the operational feasibility will be explored, as well as its effectiveness compared to the chosen single-operation concepts in section 4.2. For the combination of single-operation concepts, the NPV values of both solutions will be combined via addition, whilst for multi-operation concepts, a new investment cost will have to be calculated. The savings per year can be added, which results in a new NPV. The score for NPV is calculated similarly, with an increased limit. Instead of an NPV of €500'000 giving a score of 5, an NPV of $500000 \cdot n$ will receive a score of 5, with n being the number of operations accounted for. For example, for the combination of PCA, GPU, Chocks, and FOD, an NPV of €2'000'000 will receive a score of 5, as it covers 4 different operations. For the RAMS, flexibility and TRL, the average score will be taken of the concepts used for both single- and multi-operation combinations.

4.9.2. FOD check and technical inspection

For both FOD detection and technical inspection, an advanced detection system is required that can detect and classify both FOD and any damage. Since the systems used for this purpose are very similar, they can be combined fairly easily. The main difference in the two operations is that the FOD check requires the ability to clean up the FOD as well (*FOD-02*). Operationally, the FOD check occurs some time before the aircraft arrives, and as such, an AGV can easily perform both tasks sequentially. In Table 4.14, the trade-off analysis can be found, with the justifications in Table B.5.

Table 4.14: Trade-off analysis multi-operation FOD check + Technical Inspection

	Net Present Value [40%]	**RAMS [25%]**	**Flexibility [20%]**	**TRL [15%]**	**Weighted Average**
Single-Operation	Green 4.55	Light Green 4	Green 4.5	Light Green 3.5	Light Green 4.25
Multi-Operation	Yellow 2.83	Light Green 4	Green 5	Yellow 3	Light Green 3.58

From the table, it can be seen that whilst the flexibility increases slightly, the NPV is severely reduced due to the lack of savings produced by the AGV. It can therefore be determined that this combination is not better than the specialised concepts. As flexibility is the only criterion which has a slightly higher score for the multi-operation concept, the trade-off is also practically impervious to changes in criterion weights. As for score changes, a very large increase in NPV for the multi-operation concept is required before this becomes the better option.

4.9.3. GPU and PCA connection

Since the technology required for GPU connection and PCA is very similar, an AGV that can do both is an obvious combination. Since the PCA connection is done after the GPU connection, no obvious operational conflicts exist. In Table 4.15, the trade-off analysis can be found, with the justifications in Table B.6.

Table 4.15: Trade-off analysis multi-operation GPU and PCA connection

	Net Present Value [40%]	**RAMS [25%]**	**Flexibility [20%]**	**TRL [15%]**	**Weighted Average**
Single-Operation	Yellow 2.76	Yellow 3	Green 5	Red 1	Yellow 3.00
Multi-Operation	Yellow 2.83	Yellow 3	Green 5	Red 1	Yellow 3.03

Logically, the RAMS, flexibility, and TRL scores are the same, since the chosen single-operation concepts use AGVs as well. Since both the GPU and PCA connection AGVs do not generate any savings, the difference in NPV is only present due to the difference in investment cost. For this, the single-operation concepts average a cost of €120’000 per ramp, whilst the multi-operation concept averages a cost of around €87’500 per ramp due to the decrease in total AGVs required. It can therefore be determined that combining these tasks into one AGV is preferable. As the only real difference is in investment cost, the trade-off is only sensitive to changes in this area as well. As the costs are fairly similar, however, the trade-off can be deemed sensitive.

4.9.4. GPU and PCA connection, chock placement, and FOD check

Next to the GPU and PCA connection operation, the chock placement and FOD check can be added as well. It should be noted that this will require the AGV to be fast enough to place the chocks and connect the GPU cable before the anti-collision lights turn off. In this case, this is assumed to be true. In Table 4.16, the trade-off analysis can be found, with the justifications in Table B.7.

Table 4.16: Trade-off analysis multi-operation GPU and PCA connection, chock placement, and FOD check

	Net Present Value [40%]	**RAMS [25%]**	**Flexibility [20%]**	**TRL [15%]**	**Weighted Average**
Single-Operation	Yellow 3.07	Light Green 3.5	Green 4.5	Orange 2	Yellow 3.30
Multi-Operation	Yellow 2.86	Yellow 3	Green 5	Orange 1.5	Yellow 3.12

Whilst the weighted average scores are similar, the slightly higher flexibility does not warrant the reduction in NPV, RAMS and TRL. Therefore, it is clear that this combination is not practical. It should be noted, though, that the differences in scores are small and that the trade-off therefore also seems fairly sensitive to changes in scores. As 4 different concepts are used, however, a difference of 1 in the score of one sub-part will only result in a score difference of 0.25. This means that whilst the trade-off seems sensitive to a score change, multiple subparts would need to get a score change to influence the trade-off, making it significantly less sensitive.

4.9.5. All operations

Finally, another interesting concept is to analyse a concept that can perform all operational tasks. It should be noted that this does cause operational conflicts, and as such, two of these AGVs will need to be present to execute the turnaround. In Table 4.17, the trade-off analysis can be found, with the justifications in Table B.8.

Table 4.17: Trade-off analysis multi-operation of all operations

	Net Present Value [40%]	**RAMS [25%]**	**Flexibility [20%]**	**TRL [15%]**	**Weighted Average**
Single-Operation	Light Green 3.90	Light Green 3.83	Green 4.5	Yellow 2.83	Light Green 3.84
Multi-Operation	Yellow 2.80	Yellow 3.17	ForestGreen 5	Orange 1.83	Yellow 3.19

As can be seen from the table, combining all operations into one singular concept is highly undesirable, with a significantly lower NPV, RAMS and TRL. With the significant difference in score, the trade-off is also deemed insensitive to changes in both score and criterion weight.

4.10. Conclusion and final concept

From section 4.9, it can be determined that only the combination of GPU and PCA connection is preferable to a combination of single-operation concepts. With this, a final overview of chosen concepts can be created, which also answers research sub-question 3: "Which combination of single- and multi-operation automated concepts provides the best potential performance?", and can be seen in Table 4.18. The total investment cost per ramp equals €762'000, and the total NPV €1'225'232.

Table 4.18: Overview of final concepts

Operation	**Solution**	**Net Present Value [40%]**	**RAMS [25%]**	**Flexibility [20%]**	**TRL [15%]**	**Weighted Average**
Chock Placement	Rotating Chocks	Light Green 3.94	Light Green 4	Yellow 3	Yellow 3	Light Green 3.63
GPU & PCA connection	Multi-Op. AGV	Yellow 2.83	Yellow 3	Green 5	Red 1	Yellow 3.03
Cone Placement	Virtual walls	Green 4.86	Green 5	Green 5	Green 5	Green 4.94
Technical Inspection	Fixed cameras	Green 5.00	Light Green 4	Light Green 4	Light Green 4	Light Green 4.40
FOD Check	Optical + Radar AGV	Yellow 2.84	Light Green 4	Green 5	Yellow 3	Light Green 3.59

From the table, it can be seen that only the TRL of the GPU and PCA connection AGV scores low. As the TRL is the least important criterion, this also means that for this preliminary analysis, the final concept is deemed feasible, and with a high total NPV of more than a million euros per ramp, even profitable.

5

Operational Impact Analysis

With the final concept known, further analysis can be done on the impact of automating the turnaround process. In this chapter, the final research sub-question ”How would an automated arrival and departure process affect ground handling activities, and what are the key operational risks?” will be investigated. To answer this question, multiple effects and consequences occurring from a transition to fully automated operations must be analysed. This includes an analysis of the effects on the operational schedule and spatial planning, but for example also the communication methods used. Finally, the new operational risks coming from an automated operation must also be investigated. To summarise, the following aspects will be investigated in this chapter:

1. The effect automation has on the operational schedule
2. The effect automation has on the spatial planning and potential new physical conflicts
3. The new human-robot interactions occurring during the transition towards a fully automated operation
4. The new robot-robot interactions occurring during a fully automated operation
5. The methods used to solve anomalies and malfunctions in a fully automated environment
6. The new operational risks emanating from the final concept

Each of these new effects of consequences occurring from the transition to an automated turnaround will be analysed in its own section. All of these combined will answer the research sub-question.

5.1. Scheduling changes due to automation

When the turnaround process is automated, scheduling changes are inevitable. As such, it is important to investigate the original schedule and examine the effects the automation has on the operational schedule. Not only can the order of certain operations change, but the dependencies can also vary, or operations can be eliminated from the schedule. The following changes can be found: The rear wheel chock placement required the anti-collision lights to be turned off, since ground personnel would have to approach the engines when placing them. With the automated solution of rotating chocks, this is no longer required, and as such, both the front and rear chocks can be deployed immediately after the aircraft is stationary. For the GPU and PCA connection, no scheduling changes are present, due to the automated vehicles having similar restrictions as ground personnel. With the use of virtual walls instead of safety cones, the operation can be performed immediately after the aircraft is stationary, since, similarly to the wheel chocks, the operation is no longer dependent on the anti-collision lights being turned off. The FOD check is still performed in a similar manner and before the aircraft arrives, and as such, automation of this operation does not inflict any scheduling changes. With the focus on arrival and departure operations, no further scheduling changes are present for this final concept, though more changes are expected when automating the other operations, which are out of the scope of this thesis. The full adjusted operations schedule can be found in Figure 5.1.

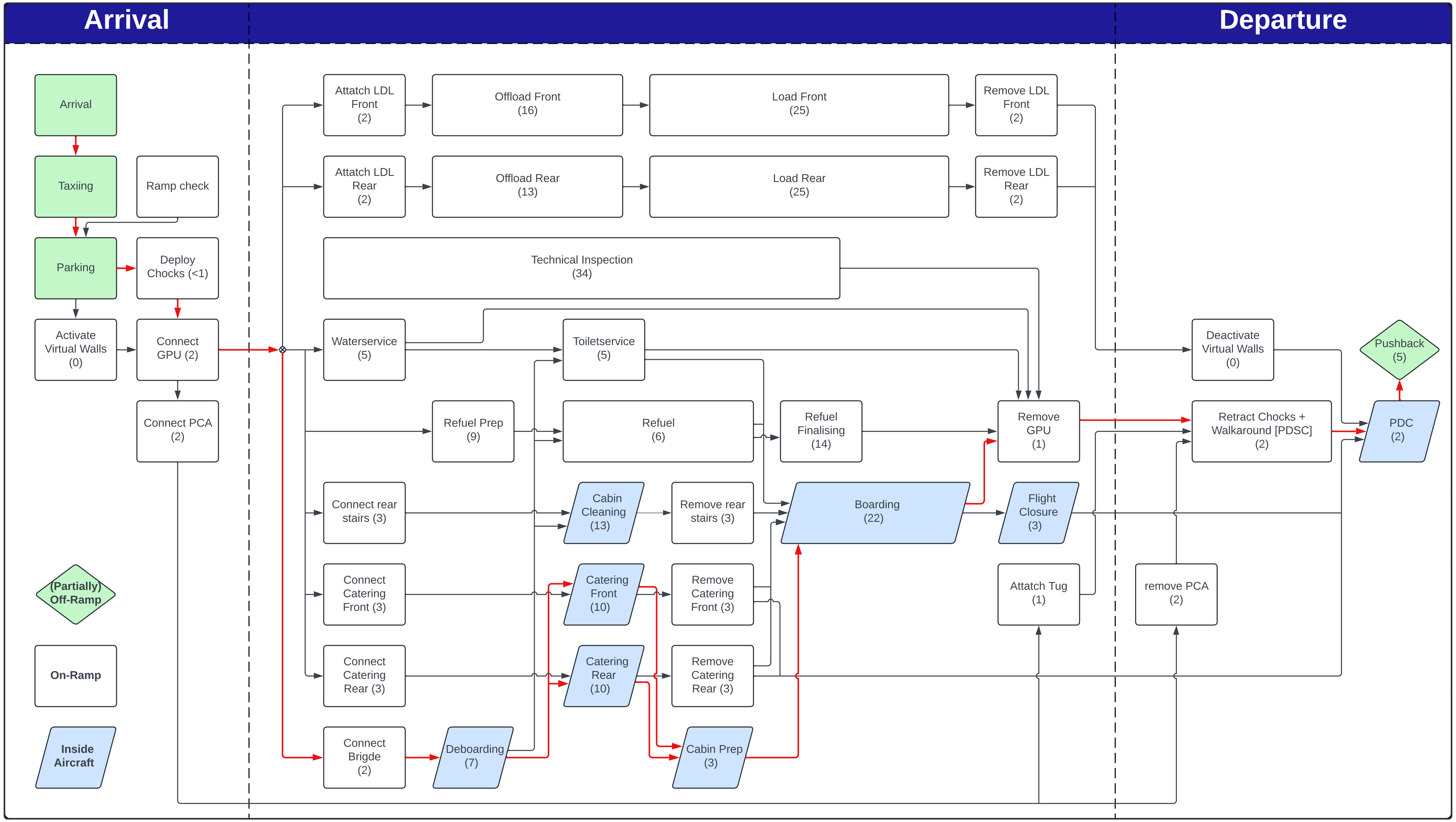

Figure 5.1: Hierarchical flow chart of the final concept operations with the critical path in red.

From this figure, the changes in the arrival and departure process can clearly be seen. The chocks can be deployed without having to wait for the anti-collision lights to be turned off, and with the near instant activation of the virtual walls, all other operations below the wing, such as the attachment of the LDLs, no longer have to wait for the cones to be placed. With a reduction in operational duration of 37.76 seconds from wheel chock deployment, 30 seconds from the use of the virtual wall system, and 105 seconds from the automated technical inspection (see Appendix B), the fully automated turnaround duration can be assumed to be 172.76 seconds shorter.

5.2. Spatial analysis

With the final concept, new infrastructure is created, and multiple robots will be present on the ramp. To ensure it is possible to utilise all the chosen concepts simultaneously, and no physical conflicts exist, a spatial analysis should be performed. The vehicles used in other operations outside of the arrival and departure phase are not present during the arrival or departure process, and do not approach the engines or landing gear. Therefore, no conflicts between the automated concepts and the manual operations outside of the scope of this thesis are expected. With this in mind, only physical conflicts between the chosen concepts need to be analysed. The concepts chosen and their physical locations can be seen in Table 5.1.

Operation	Concept	Physical location
Chock placement	Rotating chocks	In-ground at nose and main gear
GPU & PCA connection	Multi-Op. AGV	Free-roaming AGV
Cone placement	Virtual walls	Virtual / None
Technical inspection	Fixed cameras	On terminal or truss structure and in-ground near the engines
FOD check	Optical + radar AGV	Free-roaming AGV

Table 5.1: Final Concepts Physical Locations

As the cone placement is replaced by a virtual system, no conflicts will occur between this and other systems. From Table 5.1, the following possible physical conflicts between the automated concepts can be identified:

- GPU & PCA AGV with rotating chocks
- GPU & PCA AGV with in-ground technical inspection cameras
- GPU & PCA AGV with FOD AGV
- FOD AGV with rotating chocks
- FOD AGV with in-ground technical inspection cameras

As the FOD check has to be performed before the aircraft arrives, the FOD AGV should not have any physical conflicts with the GPU & PCA AGV, which operates at a later stage during the turnaround. The FOD AGV should not have any physical conflicts with the in-ground technical inspection cameras or rotating chocks, as both should be fully retracted during the FOD check. This leaves the possible physical conflicts between the GPU & PCA AGV with the rotating chocks and in-ground technical inspection cameras for further analysis.

GPU & PCA AGV and rotating chocks

As seen in Figure 2.5, the GPU connection point is right next to the nose gear, resulting in possible conflicts between the GPU & PCA AGV and the rotating chocks when connecting the GPU cable. As the GPU & PCA AGV will be situated on the side of the rotating chocks, only the width of the rotating chocks is of importance for this interaction. Theoretically, the chocks only need to be as wide as the aircraft tyre, but as the aircraft might not be parked perfectly each time, some margin will be required. With a conservative mis-parking tolerance of 0.3 m,[64] the rotating chocks must be at least offset by up to this distance. Therefore, assuming the GPU connection point is set right behind the nose landing gear, and the GPU & PCA AGV is capable of connecting the GPU cable at least 0.3 m beyond its outer footprint, the physical conflict can be bypassed.

GPU & PCA AGV and in-ground technical inspection cameras

As the PCA connection point is in the centre of the aircraft and the in-ground technical inspection cameras will need to be situated near the front of the engines, the GPU & PCA AGV should be able to avoid it using automated routing. For example, a detection algorithm or exclusion zones can be used to prevent the GPU & PCA AGV from accidentally driving into the technical inspection cameras.

To summarise, two potential physical conflicts are identified: between the GPU & PCA AGV and rotating chocks, and between the GPU & PCA AGV and in-ground technical inspection cameras. These conflicts can be resolved by designing the GPU & PCA AGV such that it can connect the GPU cable at least 0.3 m beyond its outer footprint, and adding a detection algorithm or exclusion zones, so that it will avoid any collisions with the in-ground technical inspection cameras. With these measures in place, no physical conflicts between the concepts are expected.

5.3. Human-Robot Interactions

During the development of the automated systems, a hybrid environment will be created in which both automated systems and ground personnel will work together. To ensure a smooth, efficient and, most importantly, safe turnaround, the new robots working on the stand will need to communicate with the ground personnel present. For example, a self-driving vehicle should always clearly communicate where it wants to go and signal if something is wrong. There are three different ways a robot can communicate with a person: Visually, audibly and haptically.[65] Most systems today use a combination of these three to communicate.

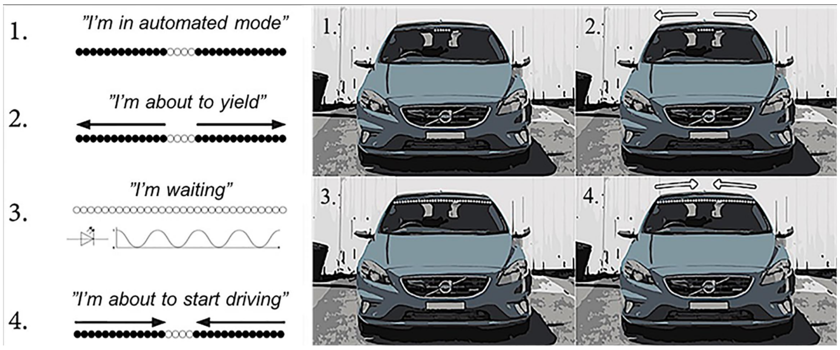

Figure 5.2: Light bar to show the intent of an AV to pedestrians.[66]

Figure 5.3: Example of a layer signal tower[1]

Visual Communication

One of the simplest and most intuitive ways for humans to interpret a system's intent is through the use of visual cues. Every day, you can find examples of this in, for example, traffic lights or the status light on your television. For robots and self-driving vehicles, simple visual cues can be used as well. For example, Habibovic et al. studied the use of visual cues to communicate the intent of the self-driving vehicle to pedestrians, examples of which can be seen in Figure 5.2.[66] AGVs driving on the stand could use a similar system to communicate their intentions, avoiding miscommunication between them and the personnel on the stand. Other automated systems can also use coloured lights or signal towers, such as the one in Figure 5.3, to communicate their status. This could be used, for example, to indicate that the system is active or when a system is encountering an anomaly and needs help.

Audible Communication

Next to visual communication, audible communication is the most common method for systems to communicate with people. An everyday example of this is a fire alarm or a notification on your mobile phone. Self-driving vehicles working on the stand can use similar communications to those used today by normal cars, such as beeps when reversing to avoid miscommunication. Other systems can also use audible signals to signal that they are finished or when an anomaly has occurred. It should be noted that personnel on the stand often wear hearing protection, causing audible signals to go unnoticed. Since the hearing protection often has integrated speakers to communicate via radio, these can be used to relay audible signals, though this is less effective due to the lack of direction. Whilst

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[1] en.wikipedia.org/wiki/Stack_light#

spatial audio can theoretically be combined with motion sensors to give a sense of direction, as is often used in virtual reality headsets, such solutions are presently impractical for apron operations due to the cost and integration complexity. Moreover, audio signals cannot be overused; otherwise, personnel will get overloaded and potentially miss important signals.[67]

Haptic Communication

A less common method for systems to communicate is through the sense of touch or haptics. Often, this is performed through vibrations, such as a phone vibrating in your pocket or a game controller vibrating when performing an action. The duration, rhythm, and strength of the vibration can be varied to communicate different things and different urgencies.[68] For aircraft turnaround, this could be used to notify personnel. For example, when an operation finishes, a short vibration can be transmitted, or a strong and long vibration for a dangerous situation. Of course, for haptic communication to be possible, each ground staff member must wear a device, such as the one proposed by Yuhang Che et Al, which investigated the usage of such a device for collision avoidance.[69] Acquiring such devices, however, also increases the cost significantly. Furthermore, the number of different signals that can be communicated through haptics is very limited before they become hard to distinguish. That said, strong haptic communication is almost always detected and is not influenced by the use of hearing protection or by it going unnoticed simply because the staff member was looking in the wrong direction or was distracted. This makes haptic communication a viable solution for an airport environment, where large amounts of noise and distractions are almost always present. Nevertheless, the effective use of haptic communication requires significant amounts of training and standardisation, as unfamiliar vibration patterns are likely to be misinterpreted by personnel.

In an airport environment, visual, audible, and haptic communications can all be used. That said, to ensure reliability of communication and to create redundancy in case one method fails, it is recommended to use at least two simultaneously, especially during potentially hazardous situations. For example, when an AGV is preparing to start moving, both a visual and an audible cue can be given, similar to how commercial cars do when they start to move in reverse. The use of haptics is more reliable, but suffers from extra integration costs and training requirements, and a limited set of distinguishable signals.

5.4. Robot-Robot Interactions

As the automated systems get implemented, robot-robot communications will occur more frequently as well. Whilst some systems will be able to operate independently, most will have to communicate with each other, for example, to avoid collisions or to indicate that the other can start its operation. The usage of effective robot-robot communication is vital to ensure efficient and safe cooperation of automated systems. Improper or delayed communication can result in conflicts, inefficiencies in the operation, collisions or unsafe situations. Information that might need to be shared between automated systems includes, for example, position data, operation progress, start/stop signals, or anomaly notifications. For robot-robot communications, two methods are possible. Firstly, they can communicate directly using device-to-device (D2D) communication.[70] Secondly, they can communicate indirectly through a centralised network, exchanging data with all connected systems, also known as the Internet of Things (IoT).[71][72]

Direct Communication (D2D)

During hybrid operations, robot-human communication systems will need to be used. These systems can also be used for robot-robot communications, for example, by designing a self-driving vehicle such that it can understand the visual and audio signals discussed in the visual and audible communication sections. Whilst this method would not require a dedicated signal system, it would require significant development to allow the robots to identify transmitted signals. With a dedicated D2D system, the automated systems can directly communicate information with each other. Whilst this does require a designated system, it is also a much more reliable method, as such communication is rarely misinterpreted, and a confirmation signal can be used to ensure proper delivery of information. The main advantage of D2D communication is that it ensures low-latency communication, which can be vital for certain safety-critical communications, such as collision avoidance. That said, it scales poorly as the number of systems increases, as it manages an increasing number of communication channels simultaneously.

Centralised Communication (IoT)

Another way to communicate is through the use of a centralised network. Since the automated systems will need to be able to communicate with the central scheduling system, regardless of the robot-robot communication method used, no extra modifications or development are needed for this method. The centralised network can then be adjusted to relay information between systems when the systems are trying to communicate with each other. Whilst this does significantly increase the transmission distances, and thus latency, the transmission speeds are sufficiently fast to not have any significant effect for most use cases, regardless of the transmission method used.[73] This method also allows the storage and analysis of vital data, from which recurring problems or anomalies can be detected, allowing for further operational improvements. A key disadvantage of fully centralised communication is that it introduces the network to a single point of failure, making the entire system vulnerable to a system failure or cyberattacks.

For aircraft turnaround operations, a hybrid communication architecture is presumably most suitable. Direct D2D communication can be used for safety-critical information, such as collision avoidance or severe anomalies, and as a backup in case of a system failure. Centralised IoT-based communication can be used during normal operations, supporting task scheduling and operation monitoring, whilst allowing further improvements to be made from the data that can be stored. This redundancy ensures robustness and resilience against any potential cyberattacks.

5.5. Malfunctions and Repairs

When robots experience an anomaly, such as a mechanical failure or a software bug, they might not be able to recover on their own. For example, if a mobile platform falls over or gets stuck, someone must come to recover it. Similarly, if a software program crashes or gets stuck in a loop due to an unexpected bug, it might need a manual reboot, which must be initiated locally. The potential severity of such failures is already evident now, with self-driving cars becoming more common. In 2023, for example, two dozen self-driving vehicles caused a gridlock in Austin, Texas, as the vehicles were waiting for each other to move out of the way.[74] Initially, when a lot of personnel are still present on the stand, many issues can be resolved by personnel already present. This becomes increasingly difficult, however, with more automation. When a lot of operations are automated, staff can be hired specifically to solve anomalies that occur during automated operations. Such staff would have a longer response time, however, increasing the delay duration. Reliability of the automated systems, therefore, becomes increasingly important as fewer personnel are used for turnaround operations.

Remote Control

To reduce the response time and thus mitigate the effect of anomalies, remote control of the automated systems could be used. For example, if an AGV gets stuck, remote control could be used to manually, but remotely, guide the AGV until it can resume its automated operations. This would significantly speed up such interventions and prevent large congestions or cascading delays. In other industries, such as container handling terminals, remote control centres are already used extensively.[75] Similar structures and setups could be used for aircraft turnaround operations, and lessons learned from other sectors could be incorporated. Remote control can also be used as an intermediate step towards full automation when full automation is not yet possible. This could be used to perform operations such as docking vehicles to aircraft, where high precision is needed, whilst simpler operations are fully automated. This would allow a reduction in the workforce needed, whilst also removing personnel from an unhealthy environment. This would also allow operators to quickly switch between vehicles, allowing ground handling personnel to be more productive as they no longer have to wait for other operations to finish. For such remote control operations, a remote control centre should be created to supervise and control the vehicles.

The increase in response time to anomalies due to the reduction of ground staff presence at the ramp clearly shows the importance of developing anomaly handling strategies. Either automated systems should be capable of self-recovery or dedicated staff should be able to, either manually or remotely, be available to recover the system. A combination of all solutions mentioned is likely to prove most effective, with automated systems having basic self-recovery capabilities, remote control being available for fast anomaly mitigation, and dedicated staff being available to solve any severe anomalies that cannot be solved automatically or remotely.

5.6. Risk Analysis

Whilst the RAMS (Reliability, Availability, Maintainability, and Safety) of the different concepts was superficially analysed in chapter 4, performing a complete risk analysis is crucial before the concepts are further developed and designed. By identifying all potential hazards and uncertainties early in the development process, failures can be anticipated and mitigated before they even occur. This increases the reliability and safety of the systems, but also reduces development costs and prevents potential costly delays. Note that the scores are not given quantitatively, and therefore are subject to some uncertainty, and the results should also be interpreted comparatively rather than as absolute values. That said, the analysis still gives valuable insights into the risks and challenges that need to be solved during development.

In this section, the results of the risk analysis performed are presented. In this analysis, the risks that come with the chosen concepts are identified and assessed. For each risk, the total risk is calculated by multiplying the likelihood by its impact, through the generally accepted methods described by Aven.[76] This is done as both severe but extremely unlikely and likely but insignificant risks pose limited operational risk, whilst risks with high likelihood and impact do. To also show what methods can be used to mitigate the identified risks, the methods described by Vose [77] are used. After identifying the risks, mitigation strategies are applied to each risk to reduce the likelihood and/or impact of said risk. For each risk, potential mitigation strategies are also identified, after which a new likelihood, impact and total risk can be calculated. Note that other mitigation strategies are, of course, always possible as well, and the mitigation strategies given are only noted to give an idea of the possible methods to mitigate the risk. Below, the different mitigation strategies as described by Vose can be found.[77]

- Accept / do nothing (because it would cost too much or there is nothing that can be done)
- Add a contingency (extra amount to budget deadline, etc., to allow for possibility of risk)
- Reduce (e.g. build in redundancy, take a less risky approach)
- Share (e.g. with a partner, contractor, providing they can reasonably handle the impact)
- Transfer (e.g. insure, back-to-back contract)
- Eliminate (e.g. do it another way)

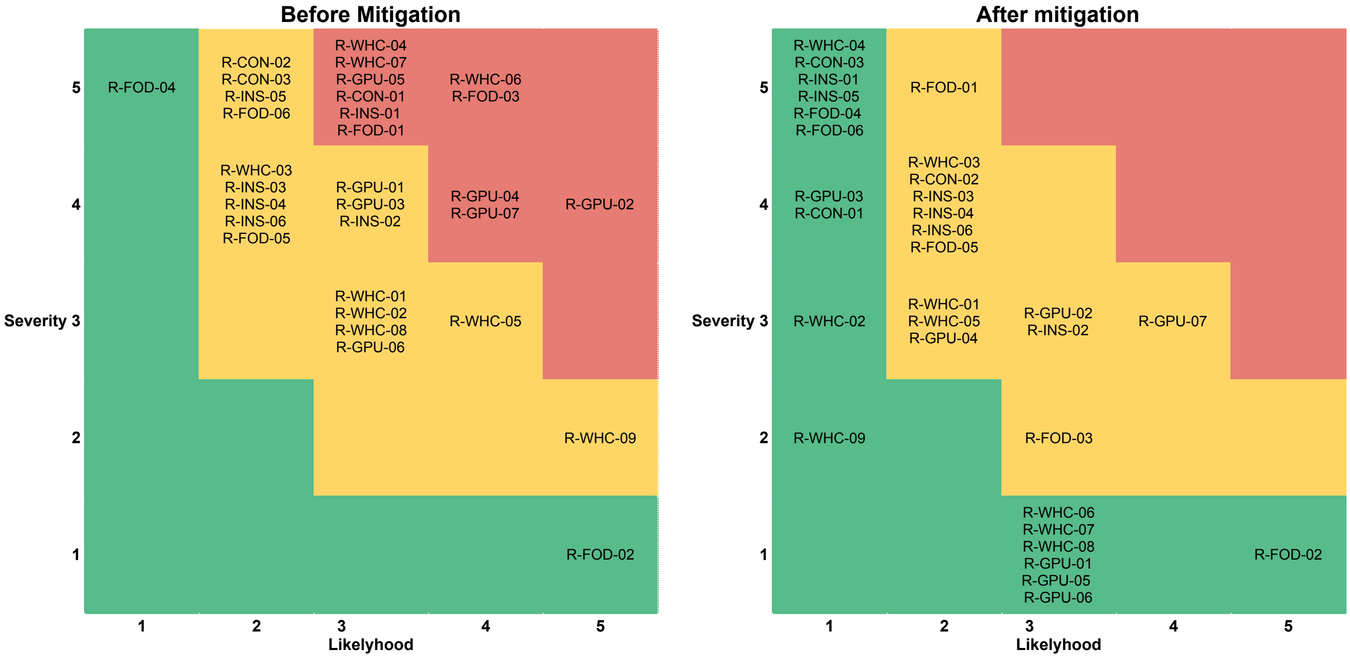
The likelihood and Impact scores are defined as shown in Table 5.2.

Table 5.2: Risk score definition

Likelihood		**Impact**	
1	Very unlikely	1	Minimal Impact - Can be solved automatically and causes no significant delay
2	Unlikely	2	Low impact - Causes some delay in the operation, but can be solved automatically
3	Possible	3	Moderate impact - Causes a delay in the operation and requires some manual intervention
4	Likely	4	Significant impact - Causes significant delays for the turnaround and requires manual intervention on location
5	Almost Certain	5	Critical impact - Causes extreme disruptions, can cause harm to personnel or passengers, or cause damage to infrastructure or aircraft

A visual summary of the risk analysis is shown in Figure 5.4, where on the left the risks are shown without mitigation strategies applied and on the right the risks with the mitigation strategies applied. From this, it can be seen that without applying mitigation strategies, there are many risks within the yellow medium-risk region and even eleven risks within the red critical region. Applying the mitigation strategies results in many more risks in the green acceptable region, and none in the red critical region. That said, some risks, such as R-GPU-07 (AGV fails to find a path due to congestion or gets stuck) and R-FOD-01 (Robot misses FOD, causing potential hazards), are still in the yellow medium-risk region and border the critical region. These risks are therefore also of most importance and require particular attention during the development of the concepts. In Table 5.3, the full risk analysis is presented. In this table, the following items are covered for each risk:

- **Risk ID**: Each autonomous operation or subsystem is assigned a unique risk ID (e.g., R-REF-01, R-CAT-01).
- **Risk Description**: A brief description of the potential risk.
- **(LH) Likelihood**: This column shows the likelihood of the risk occurring on a scale from 1 (very unlikely) to 5 (almost certain).
- **(I) Impact**: The severity of the risk's impact, again rated on a scale from 1 (minimal impact) to 5 (critical impact).
- **(T) Total risk**: The product of likelihood and impact, used to prioritise risks based on their criticality.
- **Likelihood mitigation**: Actions aimed at reducing the likelihood of the risk occurring.
- **Impact mitigation**: Steps to reduce the impact of a risk if it occurs.
- **Strategy**: The overall approach to managing the risk, such as reducing the likelihood, transferring responsibility, or accepting the risk with existing measures.
- **(NL) New likelihood**: The likelihood score after mitigation actions.
- **(NI) New Impact**: The impact score after mitigation actions.
- **(NT) New total risk**: The total risk after mitigation actions.



Before Mitigation

	1	2	3	4	5
5	R-FOD-04	R-CON-02 R-CON-03 R-INS-05 R-FOD-06	R-WHC-04 R-WHC-07 R-GPU-05 R-CON-01 R-INS-01 R-FOD-01	R-WHC-06 R-FOD-03	
4		R-WHC-03 R-INS-03 R-INS-04 R-INS-06 R-FOD-05	R-GPU-01 R-GPU-03 R-INS-02	R-GPU-04 R-GPU-07	R-GPU-02
Severity 3			R-WHC-01 R-WHC-02 R-WHC-08 R-GPU-06	R-WHC-05	
2					R-WHC-09
1					R-FOD-02

Likelyhood

After mitigation

	1	2	3	4	5
5	R-WHC-04 R-CON-03 R-INS-01 R-INS-05 R-FOD-04 R-FOD-06	R-FOD-01			
4	R-GPU-03 R-CON-01	R-WHC-03 R-CON-02 R-INS-03 R-INS-04 R-INS-06 R-FOD-05			
Severity 3	R-WHC-02	R-WHC-01 R-WHC-05 R-GPU-04	R-GPU-02 R-INS-02	R-GPU-07	
2	R-WHC-09		R-FOD-03		
1			R-WHC-06 R-WHC-07 R-WHC-08 R-GPU-01 R-GPU-05 R-GPU-06		R-FOD-02

Likelyhood

Figure 5.4: Matrix visualisation of Table 5.3

To give an example on the methodology on the scoring, risk R-GPU-04 can be used. The risk here is that the GPU & PCA AGV will be unable to perform its operation due to extreme rain, snow, fog, or other weather effects blocking the sensors from working properly. As such adverse weather will occur at some point, a high likelihood score is appropriate. That said, such adverse weather will not occur on a very regular basis, a score of 5 is not warranted. As such, a likelihood score of 4 is given. If this anomaly occurs, the operation will need to be performed completely manually, but as the AGV will simply come to a halt, no harm to personnel or damage to infrastructure or the aircraft is to be expected. As such, a score of 4 is given. This results in a total score of $4 \cdot 4 = 16$. For this risk, both the likelihood and the impact can be mitigated, by using less weather dependent sensors such as radar, and allowing the AGV to be manually operated remotely in case it does fail. This reduces the scores to 2 and 3 for likelihood and impact respectively, resulting in a mitigated total score of 6. All other risks are analysed in similar fashion.

Table 6.2: *Risk Identification & Mitigation*

Risk ID	Risk Description	LH	I	T	Likelihood Mitigation	Impact Mitigation	Strategy	NL	NI	NT
Wheel Chock										
R-WHC-01	Aircraft does not park on the system, meaning it cannot be used	3	3	9	Increase chock system width, allowing for more margin		Reduce	2	3	6
R-WHC-02	Chocks fail to rotate upwards, resulting in normal chocks being required	3	3	9	Add a secondary actuator capable of deploying the chock		Reduce	1	3	3
R-WHC-03	Rotating mechanism fails and gets jammed	2	4	8			Accept	2	4	8
R-WHC-04	Chocks fail to stay in position and retract whilst aircraft is parked	3	5	15	Add a ratchet and pawl mechanism or hydraulic locking unit, preventing unwanted retraction		Reduce	1	5	5
R-WHC-05	FOD gets stuck in the rotating mechanism	4	3	12	Close gaps between mechanisms to prevent ingestion		Reduce	2	3	6
R-WHC-06	Chocks are too slippery due to rain or ice to hold the aircraft in place	4	5	20		Rotate chocks to a high angle to prevent movement when chocks are slippery	Reduce	3	1	3
R-WHC-07	Deployment sensor falsely indicates a correct deployment	3	5	15		Add redundant sensors and use triple modular redundancy to determine and isolate a faulty sensor	Reduce	3	1	3
R-WHC-08	Deployment sensor falsely indicates an incorrect deployment	3	3	9		Add redundant sensors and use triple modular redundancy to determine and isolate a faulty sensor	Reduce	3	1	3
R-WHC-09	Unused deployed chocks causes a tripping hazard for ground staff	5	2	10	Automatically retract chocks if they do not feel any resistance		Reduce	1	2	2
GPU & PCA										

R-GPU-01	The robotic arm misaligns with the port on the aircraft, preventing a connection	3	4	12		Automatically detect misconnection and automatically restart the connection process	Reduce	3	1	3
R-GPU-02	GPU/PCA cable gets stuck or pinched	5	4	20	Add a proper cable management system and routing constraints	Automatically detect snags/pinches and attempt to return to start position	Reduce	3	3	9
R-GPU-03	Incorrect aircraft type inserted, causing misalignment	3	4	12	Add automated aircraft identification redundancy via QR/AR markers and airline schedules		Reduce	1	4	4
R-GPU-04	Rain, snow, fog or other weather effects block the sensors from working properly	4	4	16	Use less weather dependent sensors such as radar to limit the effect of weather	Allow remote operations of the AGV in case of bad weather	Reduce	2	3	6
R-GPU-05	Deployment sensor falsely indicates a correct deployment	3	5	15		Add redundant sensors and use triple modular redundancy to determine and isolate a faulty sensor	Reduce	3	1	3
R-GPU-06	Deployment sensor falsely indicates an incorrect delpoyment	3	3	9		Add redundant sensors and use triple modular redundancy to determine and isolate a faulty sensor	Reduce	3	1	3
R-GPU-07	AGV fails to find a path due to congestion or gets stuck	4	4	16		Allow for remote operations of the AGV	Reduce	4	3	12
Cones										
R-CON-01	Incorrect aircraft type inserted, making collisions possible	3	5	15	Add automated aircraft identification redundancy via QR/AR markers and airline schedules	Add a hard stop to all AGVs when they are about to collide with an unknown object	Reduce	1	4	4
R-CON-02	An AGV ignores the geofence	2	5	10		Add a hard stop to all AGVs when they cross the geofence	Reduce	2	4	8
R-CON-03	Ground crew present for an anomaly collides with aircraft due to lack of cones	2	5	10	Increase training for ground crew specialised in anomalies		Reduce	1	5	5
Inspection										

R-INS-01	Robot misses dents, crash or other damage on the aircraft	3	5	15	Implement a confidence score, requiring human review if too low		Reduce	1	5	5
R-INS-02	Robot incorrectly marks harmless features such as paint scratches as damage	3	4	12		Automatically flag and remotely accept or dismiss findings from the robot	Reduce	3	3	9
R-INS-03	AGV fails to find a path due to congestion or gets stuck	2	4	8			Accept	2	4	8
R-INS-04	Rain, snow, fog or other weather effects block the sensors from working properly	2	4	8			Accept	2	4	8
R-INS-05	Robot is hacked, spoofed or disabled, impacting the safety	2	5	10	Ensure strong encryption and secure communication for detections		Reduce	1	5	5
R-INS-06	Battery depletes before the robot can finish its task	2	4	8			Accept	2	4	8
FOD Check										
R-FOD-01	Robot misses FOD, causing potential hazards	3	5	15	Outsource verification and validation of the robot to ensure reliability		Transfer	2	5	10
R-FOD-02	Robot misinterprets for example a bird as FOD causing unnecessary delays	5	1	5			Accept	5	1	5
R-FOD-03	Robot detects FOD, but fails to remove it	4	5	20	Multi-mode pickup tools to allow for different methods of pickup	Automated check if no more FOD is detected and retry sequence	Reduce	3	2	6
R-FOD-04	A component of the robot gets loose and itself becomes FOD	1	5	5			Accept	1	5	5
R-FOD-05	Rain, snow, fog or other weather effects block the sensors from working properly	2	4	8			Accept	2	4	8
R-FOD-06	Robot is hacked, spoofed or disabled, impacting the safety	2	5	10	Ensure strong encryption and secure communication for detections		Reduce	1	5	5

This analysis demonstrates that whilst several risk items are in the critical before mitigation, all critical risks can be mitigated to acceptable levels through targeted design choices, redundancy, and operational procedures. As such, it can be concluded that, with the right risk mitigation strategies implemented, the final concepts chosen can be implemented in a safe and efficient manner.

5.7. Conclusion

In this chapter, the fourth research sub-question, “How would an automated arrival and departure process affect ground handling activities, and what are the key operational risks?”, was addressed. To answer this question, the impact of the final concept on operational scheduling, congestion, and communication was analysed. In addition, the handling of malfunctions and repairs, including the use of remote control, was investigated, followed by a structured risk analysis.

From these studies, it was determined that whilst some changes are to be expected in the schedule, no significant modifications are present. Using the selected automated systems, an average turnaround time reduction of around 173 seconds was found. Similarly, no large modifications were deemed to be required for the spatial deployment of the selected concepts. For human-robot communication, a combination of visual, audible and haptic is recommended, as the reliance on only one type of communication can lead to misinterpretation or signals going unnoticed. For robot-robot communications, the usage of a hybrid communication architecture, using both direct D2D and indirect centralised communication, is deemed most suitable. This allows for both direct safety-critical communication and data storage and analysis, whilst ensuring robustness and cyberattack resilience through redundancy.

Through the study on malfunctions, repairs, and remote control, it was determined that with an increase in automation, dedicated personnel will be required to resolve anomalies that occur during automated operations. In some cases, a remote control method can be used as well to solve anomalies more efficiently. Finally, a risk analysis was performed, which identified 11 critical risks propagating from the chosen concepts. Through the application of appropriate mitigation strategies, all of these critical risks were reduced to acceptable levels, indicating that the selected concepts can be implemented without introducing unacceptable operational risks.

6

Conclusion

With a research gap in automated solutions for aircraft turnaround operations, especially for the arrival and departure operations, the objective of this thesis was to further the research on this topic, with a focus on the performance of a multi-operation automated vehicle compared to specialised single-operation systems, and the implications that automated systems could have. With this, the main research question: ”How do multi-operation automated systems compare to single-operation automated systems in aircraft turnaround, and what are the implications for turnaround operations?” was investigated. To answer this question, four different research sub-questions had to be answered first: ”What are the key operations involved in aircraft turnaround operations, and how are they currently scheduled and managed at airports?” ”How can the financial impact of changes in turnaround time be modelled and quantified?” ”Which combination of single- and multi-operation automated concepts provides the best potential performance?”, and finally ”How would an automated arrival and departure process affect ground handling activities, and what are the key operational risks?”.

6.1. Research Sub-questions

"What are the key operations involved in aircraft turnaround operations, and how are they currently scheduled and managed at airports?"

To answer this sub-question, all operations and their dependencies were identified, from which it was found that the passenger services and front baggage loading paths took up the most time. Next to this, the operational dependencies and relations and the current systems used to perform these operational tasks were investigated. From this, it was determined that practically all operations are done nearly fully manually. To understand how these schedules were managed, the different communication methods used were explored, and the use of AI and computer vision to communicate was investigated. From this, it was clear that, whilst not yet used extensively, the usage of computer vision and digital communication can significantly improve turnaround performance and reliability.

"How can the financial impact of changes in turnaround time be modelled and quantified?"

For this research sub-question, two models were created that can calculate the cost or value of an increase or decrease in turnaround time: one based on literature data, and one on actual flight data. Though significantly less computationally heavy, the model based on literature data was deemed insufficient due to insufficient accuracy. With the selected model, it was determined that, depending on the aircraft types a ramp commonly services, between €34.8 and €177.94 can be saved on average per flight for every minute the turnaround time is reduced.

"Which combination of single- and multi-operation automated concepts provides the best potential performance?"

With the financial model created previously, and in combination with analyses into RAMS, flexibility and TRL, trade-offs could be made for different automated systems. From these trade-offs, a rotating chocks system for chock placement, a multi-operation AGV for GPU and PCA connections, virtual walls for cone placement, fixed cameras for technical inspection, and, finally, an optical- and radar-equipped AGV for FOD detection were chosen. Whilst the flexibility of multi-operation systems is often higher, their reliability and net present value are often significantly lower, resulting in a multi-operation solution only being desirable for the GPU and PCA connection operation. The total investment cost per ramp for the selected concepts equals €762’000, and the total NPV is €1’225’232. Indicating that whilst a large investment is needed, a large return on investment can be expected within 10 years as well.

"How would an automated arrival and departure process affect ground handling activities, and what are the key operational risks?"

Through analyses of the effect automated turnarounds have on the operation schedule, congestion, and communication, it was found that whilst some minor changes will be required, especially for robot-human and robot-robot communication methods, the implications are manageable and foreseeable. An average reduction in turnaround time of around 173 seconds was found with the use of the selected concepts.

6.2. Main Research Question

With these results in place, the main research question, ”How do multi-operation automated systems compare to single-operation automated systems in aircraft turnaround, and what are the implications for turnaround operations?” can be answered. For the comparison between multi-operation automated systems and single-operation automated systems, it is clear that the usage of a multi-operation automated system is only beneficial for the GPU and PCA connection, where sufficient functional overlap is present to justify the merging of the two systems, without severely compromising reliability or performance. For all other combinations, there is either not enough technological overlap to warrant the creation of a multi-operation automated system, or the overlap results in a significantly lower RAMS or NPV score. It should be noted that, as mentioned in the discussion, more combinations could theoretically be possible when other operations such as fuelling or baggage handling are also considered. The implications the automated systems have on the turnaround operations are small for scheduling and congestion, but significant for communications. New communication methods will need to be developed to allow proper communication between robots and between robots and humans.

6.3. Implications of this study

For stakeholders, this thesis demonstrates that the methods of automation for aircraft turnaround operations should be based on multiple criteria, including (economic) performance, reliability, and flexibility. Decisions based solely on economic performance may lead to unreliable systems that can only perform in limited cases, as often specialised systems with higher economic performance have lower flexibility, whilst decisions solely based on flexibility may lead to suboptimal outcomes and longer turnaround times. Moreover, the effect concepts have on turnaround time should be accounted for, as dismissing infrastructural solutions solely on their investment cost can lead to suboptimal solutions. As demonstrated, the higher investment cost can often be recovered through savings in delay costs. The results from this thesis provide an informed approach in automating aircraft turnarounds, supporting decision-making on automation concepts and accelerating the transition to an environment that ensures occupational health and safety for ground staff.

7

Reflection

This study analysed the usage of multi-operation systems in the automation of aircraft turnaround operations and the implications of automation on turnaround operations. During this study, several limitations were encountered, which will be addressed in this chapter. Additionally, recommendations for future work are given.

7.1. Study Limitations

Operations Scoping

As not all operations in the turnaround process are investigated, potential beneficial combinations for multi-operation systems might have been missed. For example, the AGV used for GPU and PCA connection could also be used for performing the water, toilet, or fuel connection. As a result, the conclusions discerned on the suitability of multi-operation systems may not extrapolate to a full turnaround process that includes a wider range of automated tasks. For the excluded operations, the same methodology used in this study can be used to analyse and select single-operation and multiple-operation concepts.

Delay Cost calculations

For the delay cost calculations made in chapter 3, the delay costs from the report made by the Department of Transport Studies, University of Westminster, London,[44] were used. For this study, the at-gate full tactical costs were used. This means that also the delays from subsequent flights, and their costs, caused by the original delay are taken into account. This results in a slight overestimation with large delays, due to some delay costs being counted multiple times when it departs from Schiphol a second time, with a delay originating from a previous delay. With the dataset used in this study, it is not possible to fully distinguish the origin of the delays, and as such, impossible to remove this slight overestimation. Conversely, the effect of implementation on other airlines is omitted, resulting in an underestimation of the impact of automation. This, therefore, also diminishes the overestimation made due to the usage of full tactical costs.

Trade-off scoring

As most of the concepts have not been fully developed or implemented in a relevant environment, the scoring made for the trade-offs is sensitive to changes. With the sensitivity analyses made, it is clear that for some trade-offs, a higher certainty of scoring is required before a trade-off can be made with a high degree of confidence.

Risk analysis

The risk analysis made is qualitative instead of quantitative, and whilst it gives a good overview of important risks and challenges with the chosen concepts, a more thorough risk analysis is required before development is started.

Regulatory changes

No detailed investigation into regulatory changes or certifications required was performed. Failing to achieve regulatory approval can lead to significant delays, increases in costs, or even prevent certain systems from being implemented.

7.2. Recommendations for Future Work

Cascading from this study, several other studies can be performed to further the development and knowledge on turnaround automation. Below, several propositions for future work are made, split between research-oriented studies and practice-oriented works.

7.2.1. Research-oriented

Delay prevention from reliability

Whilst the reliability of a concept was taken into account for the RAMS score, the full effect of the reliability was not investigated. To gain more knowledge about this, the reliability of the current methods should be measured, after which an estimated reliability from the concepts can then be used to make a comparison. The effect can then also be implemented into the delay cost calculations made in chapter 3, giving a better estimate of the effect of reliability.

Simulation

To further help bridge the gap between conceptual analysis and practical application, a simulation-based evaluation of the full turnaround process could be developed. This model could, for example, test various automation levels and scheduling strategies, whilst tracking certain performance indicators such as turnaround time, delay propagation and mitigation, and the number of interactions between equipment.

Human–Robot Interaction effectiveness

Whilst multiple human–robot communication methods were discussed conceptually, their effectiveness was not analysed quantitatively. Future research could experimentally assess visual, audible, and haptic communication methods in airport environments, with a focus on detection rates, response times, and misinterpretation. Such a study would further support design choices for human–robot interaction in airport operations.

7.2.2. Practice-Oriented

ORL Analysis

Before the concepts can be implemented into real-life operations, many things will need to change. Infrastructural changes will need to be made to support a high number of electric vehicles, ground staff will need to receive new training to be able to work together with the new automated systems, new data infrastructures will need to be created, operational schedules will need to be adjusted, etc. To properly analyse this, a full Operational Readiness Level (ORL) analysis will need to be made. This analysis can then help bridge the gap between concept and implementation.

Staff impact

Whilst the effect on staffing costs is minimal when automating the arrival or departure process, it can have secondary effects on the ground staff. For example, reducing the amount of work the staff have to perform can reduce the workload, and as such improve staff morale. Furthermore, it can be beneficial for the ground staff's health, as they no longer have to be present near an aircraft with operating engines. Finally, automating the arrival process can also improve reliability, as the ground staff can sometimes not be present on time. Allowing the aircraft to park automatically can thus reduce stress for the ground staff as well. A further analysis will be required to determine the magnitude of these effects on the ground staff.

Gradual implementation

Rather than automating all turnaround operations simultaneously, a gradual implementation of automated systems is probable. Future studies could research phased deployment strategies, identifying which turnaround operations should be automated first, whilst ensuring a safe hybrid environment during the transition to a fully automated process. For example, it might be beneficial to focus on the most profitable automated concepts first, and wait with deploying riskier, less profitable concepts.

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A

Scientific Paper

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Multi-Operation Automated Vehicles for Aircraft Turnarounds

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Abstract— **Due to poor working conditions caused by emissions, heavy workloads, and significant staff shortages, airlines and airports are turning towards automation for a solution. While many automation developments focus on turnaround management and scheduling, research on the automated execution of turnaround operations is lacking, especially within arrival and departure operations and on the usage of multi-operation vehicles. This study aims to determine whether combining multiple operations into a single autonomous platform is operationally and financially beneficial. Task dependencies and interconnections were modelled, allowing the simulation of interactions and propagation of delays. A financial model was then developed to quantify the impact of changes in turnaround durations on delay-related costs. Based on net present value, reliability, flexibility, and technological readiness, different automated concepts developed for each operation were assessed and compared with multi-operation automated platforms. Additionally, the effects of automation on the scheduling, spatial management, and communications during aircraft turnarounds were analysed, accompanied by a risk analysis. Findings from this study indicate that the automation of arrival and departure operations can provide operational gains and positive financial returns, provided reliability performance meets the required thresholds. Multi-operation platforms enhance flexibility significantly, but may underperform in operational efficiency and financial viability. The results from this thesis provide an informed approach in automating aircraft turnarounds, supporting decision-making on automation concepts and accelerating the transition to an environment that ensures occupational health and safety for ground staff.**

I. INTRODUCTION

Between the arrival and departure of an aircraft, various operations must be performed during a so-called turnaround. This includes refuelling, baggage (un)loading, and passenger boarding, as well as smaller operations such as placing wheel chocks and connecting the aircraft to a power unit. For this, many trucks will be driving on the ramp in a well-orchestrated dance. Unfortunately, however, the working conditions on the aircraft ramp are poor: Work is often too physically demanding, especially for baggage crew,[1][2] and the ultra-fine particles (UFPs) emitted by aircraft engines are bad for the health of ground personnel.[3] Next to this, there is a large shortage of ground operations staff.[4] This shortage in staff also increases the workload, further degrading the working conditions.

Due to these poor working conditions and the significant staff shortage, KLM has invested substantially in automating ground operations.[5][6] One of the operations that KLM is working on to automate is foreign object debris (FOD) detection. FOD detection is of paramount importance to prevent debris from damaging aircraft and potentially getting sucked into aircraft engines, causing significant damage. Currently, a ground operations personnel member must check the aircraft ramp every time an aircraft comes in. To automate this, KLM has recently experimented with a robotic platform. The creation of such a robotic platform, however, raises the question of whether this robot can also help automate other ground operations, and if this is more efficient compared to separate solutions.

A. Problem Description

Whilst automated turnaround operation solutions have not been widely implemented yet, many different concepts for different turnaround operations are being developed to increase efficiency and improve the working environment. During current turnaround automation developments, however, each turnaround operation is approached individually. As such, solutions generated are specialised for one operation. Whilst this reduces the magnitude and investment since the developments get split into smaller portions, it also increases the number of systems required to perform an aircraft turnaround, which can lead to coordination problems and even congestion. An alternative could be a multi-operation system capable of completing multiple operations in the turnaround process. Unfortunately, the operational and financial impact of such a system is currently unknown, as well as how well it performs compared to single-operation systems.

B. Research Gap

Whilst many automation developments are done on turnaround management and scheduling,[7][8][9][10][11][12][13] research on the automated execution of turnaround operations is lacking. Whilst some developments and research have been done on large-scale operations such as baggage handling [5] and automated taxiing,[14] as well as FOD detection,[15][16][17][18][19][20][21] very few, if any, developments have been done on other operations such as wheel chock placement and removal, cone placement and removal, and power and pre-conditioned air (dis)connection.[22] Whilst some automated systems for similar operations exist outside the aviation industry,[23][24], no research has been done on the potential implementation of these systems for aircraft turnarounds. The research gap on small-scale operations in the turnaround process leaves a significant portion of the process reliant on manual labour. Additionally, the small amount of research and development that has been done focuses on single-operation solutions. Whilst this simplifies the development, it overlooks potential synergies that could come from combining multiple operations into a single system. Such a multi-operation system can also reduce vehicle congestion and simplify the coordination.

C. Research Objective

To fill the research gap mentioned, the automation of small-scale operations must be researched, and the performance of a multi-operation automated vehicle compared to specialised methods must be analysed. The use of such a vehicle can have secondary effects on the turnaround operation and thus might require several adjustments to other parts of the operation. Because of this, the implications such a vehicle has must also be investigated. Firstly, multiple automated vehicle concepts must be generated and broadly analysed to determine basic feasibility. To determine its performance, its financial impact, reliability, and other factors must be analysed. With this, the multi-operation concepts can then be compared to the best-performing single-operation concepts. This study evaluates whether multi-operation automated systems outperform specialised single-operation systems in aircraft turnaround processes, and assesses their operational and financial implications.

II. METHODS

The methodology comprised four components: System Analysis, Financial Impact Modelling, Concept Evaluation & Selection, and Operational Impact Analysis. Each focuses on a specific aspect of the automation of aircraft turnaround operations.

A. System Analysis

To compare the automated concepts with the current process and give an estimate of their performance, a literature study is conducted on aircraft turnaround automation and its operational and scheduling implications. The literature research is conducted through a review of industry reports, existing research, and regulatory guidelines related to airport operations. Relevant sources are gathered from platforms such as Google Scholar, Scopus, and IEEE Xplore, as well as organisations such as ICAO, IATA, and airport operators. Next to this, more information and data are gathered through observation and documentation of turnaround processes at Schiphol in person.

B. Financial Impact Modelling

To quantify the financial impact of a reduction or increase in turnaround time, data will be gathered on the current duration of tasks, after which a model will be created that calculates the financial impact of a change in turnaround time. As the changes in turnaround time are expected to be small, and therefore the addition of further flights is unexpected, only the effect on delay costs is evaluated, and allocated turnaround durations are assumed to remain unchanged. Two models are implemented, one using literature-based delay frequency and one computationally heavier model using historical KLM data.

C. Concept Development and Evaluation

Multiple design concepts for both single- and multi-operation concepts are developed, evaluated, and then compared using trade-off matrices. The most suitable combination of solutions is then selected for further analysis in the following sections. The concepts will be selected using decision matrices as described by Pugh.[25]. For each operation, the concepts will be weighed on the Net Present Value, the RAMS (Reliability, Availability, Maintainability, and Safety), the flexibility of servicing different aircraft types and stands, and finally the technology readiness level (TRL). Safety and environmental impacts will not be taken into account in these trade-offs, as all automated systems will need to be deemed as safe as current systems, as well as environmentally friendly. These will therefore be seen as a requirement, rather than a performance metric. Similarly, all concepts are assumed to be fully automated and require no human intervention during nominal operations. Therefore, staff reduction is not considered as a criterion either. After a single-operation selection has been made for all operations, Multi-operation concepts will be developed and compared with the selected single-operation concepts chosen earlier. Finally, the best combination of single-operation and multi-operation automated concepts will be chosen.

D. Operational Impact Analysis

After selecting the most suitable automated concepts, their impact on aircraft turnaround operations is analysed in more detail. This section consists of the following focused analyses:

- A scheduling study, analysing the effect that the automated systems have on the operational schedule used in aircraft turnarounds.
- A spatial analysis, analysing the spatial deployment of the automated systems, and the effect on congestion on the ramp.
- A Human-robot interaction study, looking into the effects the robot will have on human operators and how the robot should communicate its intent and anomalies to ground personnel.
- A Robot-robot interaction study, looking into the communications and data transfer methods the robots can use to transmit and share data.
- A study into the malfunctions and repairs of the chosen automated systems and the use of remote control as a semi-automated solution or as a method to solve anomalies

- A risk analysis, identifying potential hazards and uncertainties present in the chosen concepts. In this analysis, the operational risks stemming from the selected concepts will all be analysed and given a likelihood and impact score. From the multiplication of the likelihood and impact rating, a total risk score is given. Through this total risk rating, the most serious risks present can be found. Finally, possible mitigation strategies and their new likelihood and impact are determined for each risk.

Through these analyses, the implications of automated arrival and departure processes on ground handling activities are evaluated, and key operational risks are identified.

III. Results

A. System Analysis Results

The system analysis identified all operations and their dependencies, from which it was found that the passenger services and front baggage loading paths took up the most time. Next to this, the operational dependencies and relations and the current systems used to perform these operational tasks were investigated. From this, it was determined that practically all operations are done nearly fully manually. To understand how these schedules were managed, the different communication methods used were explored, and the use of AI and computer vision to communicate was investigated. It was clear that, whilst not yet used extensively, the usage of computer vision and digital communication can significantly improve turnaround performance and reliability.

B. Financial Impact Modelling Results

To calculate the financial impact of a decrease or increase in turnaround time, two models were created that can calculate the cost or value of an increase or decrease in turnaround time: one relying on data from literature, and the other relying on actual KLM flight data. The change in delay cost vs the change in turnaround time graph resulting from these models can be seen in Figure 1.

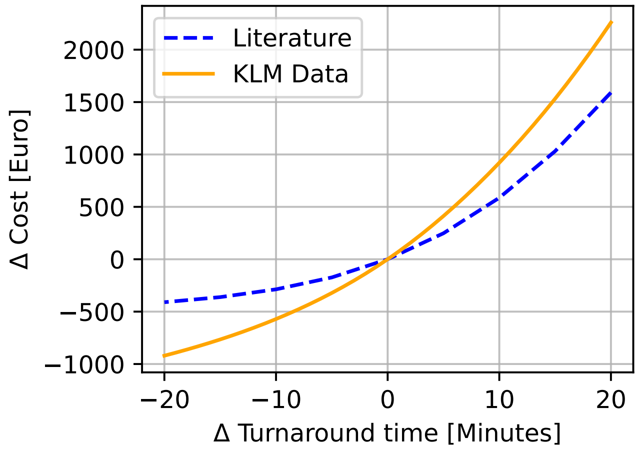


Fig. 1. Change in delay costs due to a change in turnaround time

Whilst the usage of data of literature is much less computationally heavy, it lacks data on delays larger than an hour, causing a severe underestimation in delay costs, as can be seen in Figure 1. Because of this, the more computationally heavy model using actual data is used henceforth. With this model, it was determined that, depending on the aircraft types a ramp commonly services, between €34.8 and €177.94 can be saved on average per flight for every minute the turnaround time is reduced.

C. Concept Evaluation and Selection Results

With the financial model created previously, and in combination with analyses into RAMS, flexibility and TRL, trade-offs could be made on different automated systems for each turnaround operation. From each of these trade-offs, a concept was selected. For chock placement, a rotating chock system was chosen. Whilst the investment costs are high due to the infrastructural changes required, the high performance still results in a positive NPV.

Due to the high similarity of the operations, a multi-operation AGV was selected for GPU and PCA connection, combining both operations into a single system. For the placement of safety cones, a replacement system using geofencing can be used when manually driven vehicles are no longer present on the ramp, effectively eliminating the operation. For the technical inspection of the aircraft, the usage of fixed cameras is deemed most effective due to their ability to inspect the entire aircraft almost instantaneously. Whilst the investment cost is high due to the amount of cameras needed, especially for blind spots, the reduction in turnaround time due to their performance results in an NPV of more than €800’000. Finally, an optical and radar-equipped AGV is selected for FOD detection. This combination ensures both a high detection and identification rate, whilst guaranteeing reliability in adverse weather. In Table I, all final concepts and their trade-off values can be found.

Whilst the flexibility of multi-operation systems is often higher, the reliability and net present value are often significantly lower, resulting in them being an undesirable solution. The total investment cost per ramp for the selected concepts equals €762’000, and the total NPV is €1’225’232, indicating a clear financial benefit to automation.

D. Operational Impact Results

From the operational impact studies, it was determined that whilst some changes are to be expected in the schedule, no significant modifications are present. The selected automation configuration reduced average turnaround time by 173 seconds. Similarly, no large modifications were deemed to be required for the spatial deployment of the selected concepts. For human-robot communication, a combination of visual, audible and haptic is recommended, as the reliance on only one type of communication can lead to misinterpretation or signals going unnoticed. For robot-robot communications, the usage of

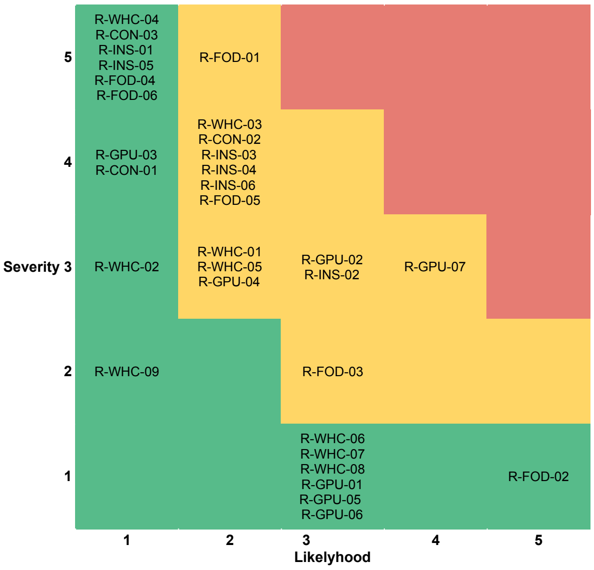
TABLE I

Overview of final concepts

Operation	**Solution**	**Net Present Value [40%]**	**RAMS [25%]**	**Flexibility [20%]**	**TRL [15%]**	**Weighted Average**
Chock Placement	Rotating Chocks	Light Green 3.94	Light Green 4	Yellow 3	Yellow 3	Light Green 3.63
GPU & PCA connection	Multi-Op. AGV	Yellow 2.83	Yellow 3	Green 5	Red 1	Yellow 3.03
Cone Placement	Virtual walls	Green 4.86	Green 5	Green 5	Green 5	Green 4.94
Technical Inspection	Fixed cameras	Green 5.00	Light Green 4	Light Green 4	Light Green 4	Light Green 4.40
FOD Check	Optical + Radar AGV	Yellow 2.84	Light Green 4	Green 5	Yellow 3	Light Green 3.59

a hybrid communication architecture, using both direct D2D and indirect centralised communication, is deemed most suitable. This allows for both direct safety-critical communication and data storage and analysis, whilst ensuring robustness and cyberattack resilience through redundancy.

Through the study on malfunctions, repairs, and remote control, it was determined that with an increase in automation, dedicated personnel will be required to resolve anomalies that occur during automated operations. In some cases, a remote control method can be used as well to solve anomalies more efficiently. Finally, during the risk analysis, which identified 11 critical risks propagating from the chosen concepts. Through the application of appropriate mitigation strategies, all of these critical risks were reduced to acceptable levels, indicating that the selected concepts can be implemented without introducing unacceptable operational risks. In figure Figure 2, the final risk matrix with mitigation strategies applied can be found.



	1	2	3	4	5
5	R-WHC-04 R-CON-03 R-INS-01 R-INS-05 R-FOD-04 R-FOD-06	R-FOD-01			
4	R-GPU-03 R-CON-01	R-WHC-03 R-CON-02 R-INS-03 R-INS-04 R-INS-06 R-FOD-05			
Severity 3	R-WHC-02	R-WHC-01 R-WHC-05 R-GPU-04	R-GPU-02 R-INS-02	R-GPU-07	
2	R-WHC-09		R-FOD-03		
1			R-WHC-06 R-WHC-07 R-WHC-08 R-GPU-01 R-GPU-05 R-GPU-06		R-FOD-02

Likelyhood

Fig. 2. Matrix visualisation of operational risks with mitigation strategies applied

IV. Discussion

A. Interpretation of System Analysis Results

Through the system analysis, it was determined that the aircraft turnaround operations are currently mostly performed manually, with passenger service and baggage loading being the most critical path. Whilst this aligns with existing literature, the system analysis further highlighted a lack of research on automation, especially for arrival and departure operations. Furthermore, the results found on digital communication and computer vision indicate a clear performance improvement capability, even without the implementation of automation.

B. Financial Implications

With €34.8 to €177.94 per flight of savings per minute of turnaround time reduction, the financial model clearly demonstrates that even small reductions in turnaround time can lead to substantial cost savings. This illustrates that, next to the importance of automation due to the poor working environment and staff shortages, the usage of automation in aircraft turnarounds can be financially beneficial as well. For stakeholders, this also demonstrates that the methods of automation for aircraft turnaround operations should be based on multiple criteria, including (economic) performance, reliability, and flexibility. Decisions based solely on economic performance may lead to unreliable systems that can only perform in limited cases, whilst decisions solely based on flexibility may lead to suboptimal outcomes and longer turnaround times. Moreover, the effect concepts have on turnaround time should be accounted for, as dismissing infrastructural solutions solely on their investment cost can lead to suboptimal solutions. As demonstrated, the higher investment cost can often be recovered through savings in delay costs.

C. Single-Operation versus Multi-Operation Automation

For the comparison between multi-operation automated systems and single-operation automated systems, it is clear that the usage of a multi-operation automated system is only beneficial for the GPU and PCA connection, where sufficient functional overlap is present to justify the merging of the two systems, without severely compromising reliability or performance. For all other combinations, there is either not enough technological overlap to warrant the creation of a multi-operation automated system, or the overlap results in a significantly lower RAMS or NPV score. It should be noted that, as mentioned in the discussion, more combinations could theoretically be possible when other operations such as fuelling or baggage handling are also considered.

D. Operational Impact and Practical Feasibility

Through analyses of the effect autonomous turnarounds have on the operation schedule, congestion, and communication, it is clear that whilst some minor changes will be required, especially for robot-human and robot-robot communication methods, the implications are manageable and foreseeable. The average reduction in turnaround time of around 173 seconds demonstrates a clear possible performance improvement, but also indicates that the impact is marginal. The implications the automated systems have on the turnaround operations are small for scheduling and congestion, but significant for communications. New communication methods will need to be developed to allow proper communication between robots and between robots and humans, and prevent miscommunication or missed signals. Finally, the risk analysis indicates that the selected concepts can be implemented without introducing unacceptable operational risks, as long as mitigation strategies are applied during the development of the selected concepts.

E. Limitations of the Study

As not all operations in the turnaround process are investigated, potential beneficial combinations for multi-operation systems might have been missed. As a result, the conclusions discerned on the suitability of multi-operation systems may not extrapolate to a full turnaround process that includes a wider range of automated tasks.

For the delay cost calculations made, at-gate full tactical costs were used. This also results in a slight overestimation with very large delays, due to them being counted multiple times. With the dataset used in this study, it is not possible to fully distinguish the origin of the delays, and as such, impossible to remove this slight overestimation. Conversely, the effect of implementation on other airlines is omitted, resulting in an underestimation of the impact of automation. This, therefore, also diminishes the overestimation made due to the usage of full tactical costs.

As most of the concepts have not been fully developed or implemented in a relevant environment, the scoring made for the trade-offs is sensitive to changes. From a sensitivity analysis, it is clear that for some trade-offs, a higher certainty of scoring is required before a trade-off can be made with a high degree of confidence.

No detailed investigation into regulatory changes or certifications required was performed. Failing to achieve regulatory approval can lead to significant delays, increases in costs, or even prevent certain systems from being implemented.

F. Implications for Future Research

To further help bridge the gap between conceptual analysis and practical application, a simulation-based evaluation of the full turnaround process could be developed. This model could, for example, test various automation levels and scheduling strategies, whilst tracking certain performance indicators such as turnaround time, delay propagation and mitigation, and the number of interactions between equipment.

Whilst multiple human–robot communication methods were discussed conceptually, their effectiveness was not analysed quantitatively. Future research could experimentally assess visual, audible, and haptic communication methods in airport environments, with a focus on detection rates, response times, and misinterpretation. Such a study would further support design choices for human–robot interaction in airport operations.

Before the concepts can be implemented into real-life operations, many things will need to change. Infrastructural changes will need to be made to support a high number of electric vehicles, ground staff will need to receive new training to be able to work together with the new automated systems, new data infrastructures will need to be created, operational schedules will need to be adjusted, etc. To properly analyse this, a full Operational Readiness Level (ORL) analysis will need to be made. This analysis can then help bridge the gap between concept and implementation.

Rather than automating all turnaround operations simultaneously, a gradual implementation of automated systems is probable. Future studies could research phased deployment strategies, identifying which turnaround operations should be automated first, whilst ensuring a safe hybrid environment during the transition to a fully automated process.

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B

Concept Decision Matrices

B.1. Wheel Chock Placement

Table B.1: Trade-off analysis wheel chock placement

	Net Present Value [40%]	**RAMS [25%]**	**Flexibility [20%]**	**TRL [15%]**	**Weighted Average**
Integrated Chocks	Red 1	Light Green 4	Red 1	Orange 2	Orange 1.90
Pushback Trucks	Red 1	Light Green 4	Light Green 4	Yellow 3	Yellow 2.65
Rotating Chocks	Light Green 3.94	Light Green 4	Yellow 3	Yellow 3	Light Green 3.63
Rail Chocks	Yellow 3.26	Light Green 4	Yellow 3	Yellow 3	Yellow 3.35
Chocks Robot	Yellow 3.10	Orange 2	Green 5	Red 1	Yellow 2.89

Integrated Chocks

Net Present Value	Whilst integrating the chocks into the aircraft would generate around half a million euro of savings due to the speed at which it operates, the costs of designing, implementing and certifying will easily run into the millions. As such, the lowest score of 1 is assigned.
RAMS	With relatively few moving parts, and the fact that it will be perfectly positioned for each aircraft, the reliability of this concept is very high. That said, the maintainability is lower, as a failure could result in severe delays, since it might not be possible to simply remove it when it fails. A score of 4 is given because of this.
Flexibility	Though integrated chocks could be applied to every aircraft, they would need to be adjusted for each aircraft type due to the differences in landing gears between aircraft types. Even if the aircraft types are very similar, a thorough check and certification would be necessary to determine their compatibility. As such, a score of 1 is given.
TRL	Whilst the technology has been used in the trucking industry, it has not been used for aircraft. A TRL of 5-6 could be argued for this, but as the system will require significant changes and upscaling to be used for aircraft, a TRL of 4 is more appropriate. As such, a score of 2 is given.

Pushback Trucks

Net Present Value	Whilst improving the time to place and remove the front chocks does not affect the full turnaround time, a complete elimination of the rear chock results in a time saving of 48.76 seconds (28.6 for placement + 19.36 for removal). This results in a net saving of €68’575 per year and ramp (with 41608 flights/year, considering the 38 ramps at pier D). With a 1.5 million investment[78], an NPV of €-737’457 can be found, resulting in a score of 1.
RAMS	As the pushback trucks are self-driving, the biggest source of anomalies will occur from navigational errors. Since solving such a problem can require a member of ground staff to travel a significant distance to the truck, a remote operation system can be implemented as well. With this, most anomalies can be solved or mitigated from the control centre. That said, anomalies due to the self-driving system are likely to be frequent. With this system implemented, and with the high reliability of current pushback truck systems, a score of 4 is appropriate.
Flexibility	As demonstrated by current operations, pushback trucks can carry any aircraft type. That said, they are limited to either narrowbody or widebody aircraft due to their size and weight difference, resulting in a score of 4.
TRL	The technology of self-driving pushback trucks has been prototyped [14], but strong enough parking brakes to replace wheel chocks have not been implemented. As such, the system is not fully complete, and a TRL of 6 is appropriate, resulting in a score of 3.

Rotating Chocks

Net Present Value	Whilst improving the time to place and remove the front chocks has no effect on the full turnaround time, an operational duration of 5.5 seconds results in a time saving of 37.76 seconds. This results in €52’553 net savings per year and ramp (again taking the flights from 38 ramps at pier D). With an added cost of €300’000 for underground infrastructural changes needed and €50’000 for the rotating chocks system, an NPV of €234’307 can be found. This results in a score of 3.94.
RAMS	With a similar system already being used in the trucking industry, the system can be deemed to be reliable. Additionally, a manual override can be implemented to retract the chocks in the event of an anomaly. After this, normal chocks can still be placed manually on top of it. Even though anomalies will be rare, it is unlikely that they can be resolved remotely, and maintenance would need to be done at night to prevent ramp closure. As such, a score of 4 is assigned.
Flexibility	As the rotating chocks are integrated in the ramp, a single row will not be able to service aircraft with significant differences in wheel track widths. Aircraft of the same series, such as the B737 or A320 series, will often have different lengths and wingspans, but the same track widths. As such, a flexibility score of 3 is given.
TRL	Whilst the technology has been used in the trucking industry, it has not been used for aircraft. Whilst it will require strengthening to handle the larger weights and tire pressures of aircraft, the technology will remain largely the same. As such, a TRL of 6 is appropriate, and a score of 3 is given.

Rail Chocks

Net Present Value	Whilst improving the time to place and remove the front chocks has no effect on the full turnaround time, an operational duration of 10 seconds results in a time saving of 28.76 seconds. This results in €40’027 net savings per year and ramp (again taking the flights from 38 ramps at pier D). With an added cost of €300’000 for underground infrastructural changes needed and €80’000 for the rail chocks system, an NPV of €65’039 can be found. This results in a score of 3.26.
RAMS	With a similar system already being used in the trucking industry, the system can be deemed to be reliable. Additionally, a manual override can be implemented to retract the chocks in the event of an anomaly. After this, normal chocks can still be placed manually on top of it. Even though anomalies will be rare, it is unlikely that they can be resolved remotely, and maintenance would need to be done at night to prevent ramp closure. As such, a score of 4 is assigned.
Flexibility	As the rail chocks are integrated in the ramp, a single row will not be able to service aircraft with significant differences in wheel track widths. Aircraft of the same series, such as the B737 or A320 series, will often have different lengths and wingspans, but the same track widths. As such, a flexibility score of 3 is given.
TRL	Whilst the technology has been used in the trucking industry, it has not been used for aircraft. Whilst it will require strengthening to handle the larger weights and tyre pressures of aircraft, the technology will remain largely the same. As such, a TRL of 6 is appropriate, and a score of 3 is given.

Chocks Robot

Net Present Value	For the chocks robot, an investment of around €80’000 is required. To reduce the operational duration, 2 chock robots can be used at the same time, which can also service around 5 ramps simultaneously. This results in an investment of €32’000 per ramp. With an operation time of 40 seconds, the placement of the real chocks will be 10.6 seconds slower. For this system, it is assumed that it can operate in parallel with the walkaround and therefore only needs an activation time of around 5 seconds. This results in a turnaround time savings of 3.76 seconds and €5233 net savings per year and ramp. This in turn results in an NPV of €26’183 and a score of 3.1.
RAMS	With a small robot driving on the ramp, many things can go wrong; getting stuck on stray cables or equipment, navigational errors, dropping or failing to pick up the chocks, or even collisions with other moving vehicles. Whilst some problems, such as navigational errors, can be solved remotely, others, such as situations where it gets stuck, will require human intervention. With this high likelihood of anomalies and the requirement of human intervention, a low score of 2 is warranted.
Flexibility	The main advantage of a chocks robot is its flexibility, as it can service any aircraft and fairly easily switch between ramps. Therefore, it receives the highest score of 5.
TRL	Whilst radio-controlled (RC) cars are very common, self-driving applications are still in development, and a chocks robot will require significant strength to be able to pick up and carry the heavy chocks. Whilst a thesis has been done on this concept,[50] no further progress has been made. As such, this concept has a TRL of 3, and receives a score of 1.

B.2. GP Connection & PCA

Table B.2: Trade-off analysis GPU Connection & PCA

	Net Present Value [40%]	**RAMS [25%]**	**Flexibility [20%]**	**TRL [15%]**	**Weighted Average**
Pit System	Red 1.4	Light Green 4	Yellow 3	Red 1	Orange 2.31
Mobile AGV	Yellow 2.76	Yellow 3	Green 5	Red 1	Yellow 3.00

Pit System

Net Present Value	Whilst connecting the GPU cable is likely to take longer when using a robotic arm, it is safe to assume that it will be completed before the anti-collision lights are turned off. As the other operations will also need to wait for the anti-collision lights to turn off, the total turnaround time remains unchanged. For the removal, it is assumed that this can be done in parallel with the walk-around. Thus, no increase or decrease in turnaround time is expected. As such, the net savings are €0. With a pit installation cost of €100’000 and an extra underground infrastructure cost of €300’000, an NPV of €-400’000 can easily be found. This results in a score of 1.4.
RAMS	Connecting the cable to the aircraft is quite difficult due to the slight movements the aircraft can still have, the accuracy required, and the fact that sometimes even human staff struggle to connect it. That said, the system can easily detect that it is not plugged in correctly due to a lack of power draw. It can then simply try again to fix the problem automatically. Maintenance would need to be done at night to prevent ramp closure. With this ease of automated anomaly detection and remediation, a score of 4 can be given.
Flexibility	Whilst the robotic arm’s reach can be extended to allow it to service different aircraft types, the parking spots of different aircraft types can differ significantly, and as such, the connection point for the GPU cable. Because of this, a pit system will only be able to service aircraft that park within its reach, which will be fairly limited. This results in a score of 3.
TRL	An automated GPU connection through the use of a robotic arm on an AGV has been attempted and prototyped by the German company Neura,[79] but no further developed system exists. This results in a TRL of 3 and a score of 1.

Mobile AGV

Net Present Value	The turnaround time savings can be assumed to be similar to the pit system, and as such, the net savings are €0. With an AGV cost of €300’000, which is spread over 5 ramps, an NPV of €-60’000 can be found. This results in a score of 2.76.
RAMS	The mobile AGV version has a similar RAMS for connecting the GPU cable to the aircraft. Whilst the maintainability of this system is higher, since it can easily be moved to a maintenance area, this system also needs to drive automatically towards the aircraft, increasing the complexity and chance of anomalies. As such, a score of 3 is given.
Flexibility	As a mobile AGV can simply drive to the correct connection point, it can service any aircraft type, resulting in a score of 5.
TRL	An automated GPU connection through the use of a robotic arm on an AGV has been attempted and prototyped by the German company Neura,[79] but no further developed system exists. This results in a TRL of 3 and a score of 1.

B.3. Cone Placement

	Net Present Value [40%]	**RAMS [25%]**	**Flexibility [20%]**	**TRL [15%]**	**Weighted Average**
AGV System	Orange 2.42	Yellow 3	Green 5	Orange 2	Yellow 3.02
In-ground	Yellow 2.94	Light Green 4	Red 1	Yellow 3	Yellow 2.83
Mobile cones	Yellow 2.84	Red 1	Green 5	Yellow 3	Yellow 2.84
Virtual walls	Green 4.86	Green 5	Green 5	Green 5	Green 4.94

AGV System

Net Present Value	For the cone placement, it can be assumed that the AGV takes around 20 seconds, resulting in a decrease of around 10 seconds in turnaround time. This is mainly due to the long distances that have to be walked, which can be traversed faster with an AGV. For removal, the operation is not limiting, and thus a duration increase or decrease has no effect on the total turnaround time. With an AGV cost of €300’000, this results in €13’918 savings per year for each ramp, and an NPV of €-145’257. This gives a score of 2.42
RAMS	The AGV system will require a complex mechanism to pick up, place, and store cones, significantly reducing the reliability. To handle cones that are knocked over, a detection mechanism being able to see that a cone is on its side is required as well. All this makes for a very complex system, with many points of failure. With this in mind, a score of 3 is given.
Flexibility	Being able to move to the correct position, the AGV system can easily service any aircraft type. This does, of course, assume that the aircraft type is known and that the aircraft has parked precisely, or that the parking position is determined accurately. A score of 5 is given.
TRL	As cone placement and pickup systems already exist for highway maintenance, which increases the TRL significantly. That said, a large amount of development is needed to automate such a truck and for it to be able to flip cones in case they have tipped over. This gives it a TRL of 4, and thus a score of 2.

In-ground

Net Present Value	Since the in-ground cones only need to be raised, a new operational time of 5 seconds can be assumed. Again noting that no savings will occur during removal, a total turnaround time difference of 25 seconds is found. Like other pit systems mentioned earlier, an implementation cost of €400'000 is assumed. With €34'794 in savings per year per ramp, this gives an NPV of €-13'144, and a score of 2.94.
RAMS	Since the in-ground solution has very few moving parts, the reliability of the concept is very high. Unfortunately, when an anomaly does occur, it will need to be fixed manually. As such, a score of 4 is given.
Flexibility	As the cones need to be positioned quite precisely, the in-ground system will only be able to service aircraft with extremely similar positions of the engines and wing-tips. Even a minor difference might result in a cone or pylon being underneath the engine, for example. As a result, a flexibility score of 1 must be awarded.
TRL	An in-ground cone system is fairly simple, and can easily be derived from existing pit systems, though they do need to deploy automatically instead of being pulled out of the ground manually. Therefore, a TRL of 6 is appropriate, giving a score of 3.

Mobile cones

Net Present Value	Since the mobile cones are quite simple, a relatively small investment of €10'000 is assumed. That said, since 4 are required, this results in a cost of €40'000 per ramp. For the mobile cones, the movement speed is assumed to be similar to a human, mostly due to the instability. With that in mind, a similar operational duration can be assumed. This thus results in no savings, and an NPV of €-40'000 and a score of 2.84.
RAMS	When cones are placed or removed, no vehicles are present. In combination with the low weight of the mobile cones, this makes an advanced collision detection system redundant. Their low weight, however, also makes mobile cones prone to tipping over, which can only be solved manually. The cones can also be knocked or blown over, and their inability to recover from this makes it an extremely unreliable system. For this, the lowest score of 1 has to be given.
Flexibility	Being able to move to the correct position, the mobile cones can easily service any aircraft type. This again assumes that the aircraft type is known and that the aircraft has parked precisely, or that the parking position is determined accurately. A score of 5 is given.
TRL	Similarly to the in-ground cones, the technology enabling this system is quite simple and used in other sectors, but again, no automated versions are made, requiring some more development. Again, a TRL of 6 and a score of 3 is appropriate.

Virtual walls

Net Present Value	Since the vehicles are assumed to be AGVs for this concept, they will already be equipped with the necessary technology to make the virtual wall system possible. As such, no significant added investment is assumed. With a complete elimination of the operation, €41'753 in savings can be found per year per vop. This gives an NPV of €464'227, and a score of 4.86.
RAMS	The reliability of the use of virtual walls is very high, since the automated vehicles can be programmed to avoid the zone. Next to this, a backup mechanism can be used that stops vehicles when they are detected inside the zone. Remote driving can also be implemented to solve these anomalies remotely. Because of this, a score of 5 is given.
Flexibility	The virtual walls can be used for any aircraft type. This again assumes that the aircraft type is known and that the aircraft has parked precisely, or that the parking position is determined accurately. A score of 5 is given.
TRL	Though they are not used in airports, virtual walls and exclusion zones for AGVs are used extensively. Even smaller, less sophisticated AGVs such as robot vacuum cleaners often use them to avoid certain, often custom-set, zones. As such, a TRL of 8 and a score of 5 can be given.

B.4. Technical Inspection

Table B.3: Trade-off analysis Technical Inspection

	Net Present Value [40%]	**RAMS [25%]**	**Flexibility [20%]**	**TRL [15%]**	**Weighted Average**
Land-based	Yellow 2.80	Light Green 4	Green 5	Yellow 3	Light Green 3.57
Drones	Green 5.00	Red 1	Green 5	Green 5	Light Green 4.00
Fixed cameras	Green 5.00	Light Green 4	Light Green 4	Light Green 4	Light Green 4.40

Land-based

Net Present Value	For technical inspections, only the walkaround made by the pushback truck driver will influence the total turnaround time, as the other inspections are done in parallel with other tasks. As a robot such as Boston Dynamics spot has a movement speed similar to a person, the inspection is assumed to take a similar amount of time. With an investment cost of €150'000, the cost per ramp becomes €50'000, assuming one robot can service 3 ramps. This thus also results in an NPV of €-50'000 and a score of 2.8.
RAMS	When performing the inspection, the land-based robot can easily scan areas multiple times in case of uncertainty, increasing its reliability. Traversing over the ground does come with some risks however, such as collisions or getting stuck. Because of this, a score of 4 is given.
Flexibility	As land-based robots can simply move around, they are very flexible and can service any aircraft type. A score of 5 is thus given.
TRL	Multiple prototypes for inspection via land-based robots exist, but are not used extensively or commercially. Moreover, these lack the required obstacle avoidance active ramp operations. As such, a TRL of 6 and score of 3 is given.

Drones

Net Present Value	With their added speed, a drone can scan an aircraft much faster. Assuming a duration of 60 seconds, this saves 60 seconds on average. That said, as only around 60% of the walkarounds is actually limiting for the total turnaround time, this becomes an average reduction in turnaround time of 36 seconds. Assuming a drone can service 5 ramps and has an investment cost of €50’000 per drone, this results in an NPV of €552’918 and a score of 5.
RAMS	Whilst drones are not influenced by obstacles present on the ground, they are very dependent on good weather. During strong winds or rain, they will not be able to be used at all. This limits the usage dramatically, and thus a score of 1 has to be given.
Flexibility	As drones can move around, they are very flexible and can service any aircraft type. A score of 5 is thus given.
TRL	As drone-based inspections are being performed commercially, a TRL of 8, and score of 5 is given. It should be noted that these are only used in hangars for maintenance purposes. The limitations of this, mainly weather, are considered in the RAMS criterion, however.

Fixed cameras

Net Present Value	Assuming a new duration of 15 seconds, this results in 105 seconds of savings, and 63 seconds taking into account the fact that it is not critical every time, which in turn results in €84’382 savings per year for each ramp. With an investment cost of the cameras of €25’000, and an extra €100’000 for the instalment of cameras placed in the ground to be able to scan the underside, this results in an NPV of €813’198. As this results in a score higher than the maximum score, a score of 5 is given.
RAMS	The fact that the cameras are fixed helps in stability, but can also create some problems. If an object or vehicle is in the way, it will not be able to see the aircraft. That said, with their fast operational time, this problem is not very significant. During extreme weather, the cameras might be too far away to perform a proper inspection, but it can be assumed that they can function during most weather conditions. As such, a score of 4 is given.
Flexibility	Whilst the fixed cameras can service any aircraft, the cameras placed on the ground to scan the underside are very dependent on their positioning. As such, a flexibility score of 4 is appropriate to take this into account.
TRL	Multiple prototypes for inspection via PTZ cameras exist, but are not used extensively or commercially. Whilst these are only used in hangars, this only impacts the reliability, and not TRL. As such, a TRL of 7 and score of 4 is given.

B.5. FOD Check

Table B.4: Trade-off analysis FOD Check

	Cost [15%]	**Detection [40%]**	**Identification [30%]**	**TRL [15%]**	**Weighted Average**
Radar	Light Green 4	Light Green 4	Orange 2	Green 5	Light Green 3.55
Optical	Green 5	Orange 2	Green 5	Yellow 3	Light Green 3.50
LiDAR	Orange 2	Yellow 3	LightGreen 4	Orange 2	Yellow 3.3
Hybrid	Orange 2	Green 5	Green 5	Green 5	Green 4.55

Radar

Cost	As radar sensors are used frequently for many systems, but also for object detection on for example self driving cars, the technology is quite mature. Next to this, the radar sensors can be also very small, reducing material cost. As such, a score of 4 is given.
Detection	Whilst the minimum object size that is detectable by radar will depend on the band it uses, radar is very reliable, as it is nearly unaffected by weather such as rain or fog. It might struggle with tiny debris, but this can be solved with more expensive systems that use smaller wavelengths. Because of this, it recieves a score of 4.
Identification	Object identification through radar is not an easy task. Whilst it can easily detect an object and its location, discerning the shape of said object has proven extremely difficult. Whilst it might be possible for larger objects through the use of small bands and multiple sensors, for small objects this becomes almost impossible. As such a score of 2 has to be given.
TRL	As radar-based FOD detection systems already exist and are in active use, the highest TRL of 9 is suited, and with it, a score of 5.

Optical

Cost	Optical sensors are the cheapest sensor type discussed here. Cameras are produced on a massive scale, and for object detection, a fairly simple camera will suffice. More expensive high resolution cameras might not even be beneficial due to the added computational power required with higher pixel counts. This low cost gives it the highest score of 5.
Detection	Optical detection can be done through the use of AI, something which has been in rapid development through the last years. That said, it is still fairly unreliable compared to the other systems, giving both false positives and negatives, especially when objects are a similar colour as the ground. Moreover, it performs significantly worse during bad weather, which can prove a serious problem due to the amount of rainfall in the Netherlands. As such, a low score of 2 has to be given.
Identification	Since AI is used to detect objects, adding a second AI layer to detect the object type is not difficult. Unlike LiDAR and radar, optical sensors can also detect the different colours of an object, making the identification much easier. Next to this, if an object cannot be identified, a photo can easily be send to a control room and manually checked. The ease of application and redundancy warrants the highest score of 5.
TRL	Though FOD detection systems relying solely on optical sensors are not in active use, some, such as the one in development by Roboxi, are in the prototyping phase.[63] Thus, a TRL of 6, and a score of 3 is given.

LiDAR

Cost	LiDAR systems are the most expensive sensors discussed here, mainly due to their low usage and the high resolution required to be able to detect small objects. Because of this, a score of 2 is given.
Detection	Similarly to radar, LiDAR is weather resistant, but can also miss small debris, especially when the LiDAR system has a small resolution. Compared to radar, this is even more likely, and as such, will receive a score of 3.
Identification	Especially when using a high resolution, identification of an object through LiDAR becomes possible. That said, like radar, the smaller the object is, the more it will struggle. This is simply due to the fact that the smaller the object is, fewer lasers will hit the object. That said, object recognition is possible, as demonstrated by self driving cars using LiDAR. Furthermore, reducing the distance to the object will increase the amount of lasers hitting it, and as such make identification easier. As such, a score of 4 is given.
TRL	Whilst LiDAR detection and identification has been proven scientifically and has been used in self-driving cars, LiDAR has not been used for small object detection and identification. Because of this, only a score of 2 can be assigned, from a TRL of 4.

Hybrid

Cost	Not only does a hybrid system require the purchase of both optical and radar sensors, the integration adds cost as well, due to the added computational power required and complexity. As such, a score of 2 is given.
Detection	With the availability of both radar and optical sensors, the hybrid system has the best of both worlds: The small objects that are hard to detect for radar can be picked up by optical sensors, whilst the radar can cover in case of bad weather. Furthermore, in case of a false positive or false negative, the robot can be commanded to investigate further until both sensors agree, making false positives and false negatives a lot less likely. With this extra redundancy, the highest score of 5 is awarded.
Identification	Whilst the radar sensors of a hybrid system won't be of much help for identification, the optical sensors can easily cover for this as discussed earlier. As such, a score of 5 is given here as well.
TRL	As Xsights' FODecect system is in active use in multiple large airports, a TRL of 9, and a score of 5 is given.

B.6. FOD Check and Technical Inspection

Table B.5: Trade-off analysis multi-operation FOD check and technical inspection

	Net Present Value [40%]	**RAMS [25%]**	**Flexibility [20%]**	**TRL [15%]**	**Weighted Average**
Single-Operation	Green 4.55	Light Green 4	Green 4.5	Light Green 3.5	Light Green 4.25
Multi-Operation	Yellow 2.83	Light Green 4	Green 5	Yellow 3	Light Green 3.58

Single-Operation

Net Present Value	For the FOD agv, no savings are present, as it does not decrease the turnaround time. It should be noted that a decrease in FOD-related incidents might decrease costs, but a more thorough analysis would be needed for this. The investment cost for the technical inspection AGV of €150'000 can be taken, with an added €50'000 for the required pick-up and storage mechanism. Without any savings, this also equates to an NPV of €-200'000. Assuming it can service 5 ramps, this reduces to €-40'000. Combining this with the NPV for the fixed concept of techinical inspection of €813'198 results in an NPV of €773'198 and a score of 4.55.
RAMS	For the RAMS score of the FOD AGV concept, a score of 4 can be assumed. Whilst this is fairly arbitrary considering no alternatives are present, it is the same for both the single- and multi-operation concepts, and therefore does not influence the final result. The fixed technical inspection concept has a RAMS score of 4, giving an average score of 4.
Flexibility	The FOD AGV concept can be used for any aircraft, as the aircraft has not even arrived yet when it is active. As such, an easy score of 5 can be given for this. The fixed technical inspection concept has a flexibility score of 4, giving an average score of 4.5.
TRL	The FOD AGV is given a TRL score of 3, as prototypes exist, but also need a lot more development. The fixed technical inspection concept has a TRL score of 4, giving an average score of 3.5.

Multi-Operation

Net Present Value	As discussed for the combination of single-operation concepts, no savings are present for the FOD AGV. For technical inspection, no savings are present either. The investment cost for the technical inspection AGV of €150’000 can be taken, with an added €50’000 for the required pick-up and storage mechanism. Another €50’000 can be added for an increase in complexity, resulting in a total investment cost of €-250’000. Assuming it can service 3 ramps simultaneously, this reduces to €-83’333, which gives a score of 2.83.
RAMS	For the RAMS score of the FOD AGV concept, a score of 4 can be assumed. Whilst this is fairly arbitrary considering no alternatives are present, it is the same for both the single- and multi-operation concepts, and therefore does not influence the final result. The land-based technical inspection concept has a RAMS score of 4, giving an average score of 4.
Flexibility	The FOD AGV concept can be used for any aircraft, as the aircraft has not even arrived yet when it is active. As such, an easy score of 5 can be given for this. The land-based technical inspection concept has a flexibility score of 5, giving an average of 5.
TRL	The FOD AGV is given a TRL score of 3, as prototypes exist, but also need a lot more development. The land-based technical inspection concept has a TRL score of 3, giving an average score of 3.

B.7. GPU and PCA connection

Table B.6: Trade-off analysis multi-operation GPU and PCA connection

	Net Present Value [40%]	**RAMS [25%]**	**Flexibility [20%]**	**TRL [15%]**	**Weighted Average**
Single-Operation	Yellow 2.76	Yellow 3	Green 5	Red 1	Yellow 3.00
Multi-Operation	Yellow 2.83	Yellow 3	Green 5	Red 1	Yellow 3.03

Single-Operation

Net Present Value	The GPU and PCA AGVs both have an NPV of €-60’000. Combining these yields an NPV of €-120’000 and a score of 2.76.
RAMS	The GPU and PCA AGVs both have a RAMS score of 3, which yields a RAMS score of 3.
Flexibility	The GPU and PCA AGVs both have a flexibility score of 5, which yields a flexibility score of 5.
TRL	The GPU and PCA AGVs both have a TRL score of 1, which yields a TRL score of 1.

Multi-Operation

Net Present Value	The GPU and PCA AGVs both do not generate any savings. It can be assumed that the investment cost is increased slightly due to the added complexity to €350’000. Since it will take longer to complete both operations, the amount of ramps it can service is reduced to 4. This results in an NPV of €-87’500 and a score of 2.83.
RAMS	The GPU and PCA AGVs both have a RAMS score of 3, which yields a RAMS score of 3.
Flexibility	The GPU and PCA AGVs both have a flexibility score of 5, which yields a flexibility score of 5.
TRL	The GPU and PCA AGVs both have a TRL score of 1, which yields a TRL score of 1.

B.8. GPU and PCA connection, chock placement, and FOD check

Table B.7: Trade-off analysis multi-operation GPU and PCA connection, chock placement, and FOD check

	Net Present Value [40%]	**RAMS [25%]**	**Flexibility [20%]**	**TRL [15%]**	**Weighted Average**
Single-Operation	Yellow 3.07	Light Green 3.5	Green 4.5	Orange 2	Yellow 3.30
Multi-Operation	Yellow 2.86	Yellow 3	Green 5	Orange 1.5	Yellow 3.12

Single-Operation

Net Present Value	The GPU and PCA AGVs have an NPV of €-60’000, the rotating chocks concept has an NPV of €234’307, and the FOD AGV has an NPV of €-40’000. Combining these yields an NPV of €74’307 and a score of 3.07.
RAMS	The GPU and PCA AGVs have a RAMS score of 3, the rotating chocks concept has a score of 4, and the FOD AGV has a score of 4. Combining these yields an average RAMS score of 3.5.
Flexibility	The GPU and PCA AGVs have a flexibility score of 5, the rotating chocks concept has a score of 3, and the FOD AGV has a score of 5. Combining these yields an average flexibility score of 4.5.
TRL	The GPU and PCA AGVs have a TRL score of 1, the rotating chocks concept has a score of 3, and the FOD AGV has a score of 3. Combining these yields an average TRL score of 2.

Multi-Operation

Net Present Value	The GPU, PCA, and FOD AGVs do not generate any savings, whilst the chocks AGV generates around €5233 savings per year. An investment cost per AGV of €400’000 can be assumed, due to the high complexity and requirements such as a robotic arm and storage system. It can, however, be assumed that one AGV can perform these tasks sequentially, and service 2 ramps simultaneously on average, reducing the cost to €200’000. Using equation 4.4, an NPV of €-141’809 can be calculated, which gives a score of 2.86
RAMS	The GPU and PCA AGVs have a RAMS score of 3, the chocks AGV has a score of 2, and the FOD AGV has a score of 4. Combining these yields an average RAMS score of 3.
Flexibility	The GPU and PCA AGVs have a flexibility score of 5, the chocks AGV concept has a score of 5, and the FOD AGV has a score of 5. Combining these yields an average flexibility score of 5.
TRL	The GPU and PCA AGVs have a TRL score of 1, the chocks AGV has a score of 1, and the FOD AGV has a score of 3. Combining these yields an average TRL score of 1.5.

B.9. All operations

Table B.8: Trade-off analysis multi-operation of all operations

	Net Present Value [40%]	**RAMS [25%]**	**Flexibility [20%]**	**TRL [15%]**	**Weighted Average**
Single-Operation	Light Green 3.90	Light Green 3.83	Green 4.5	Yellow 2.83	Light Green 3.84
Multi-Operation	Yellow 2.80	Yellow 3.17	ForestGreen 5	Orange 1.83	Yellow 3.19

Single-Operation

Net Present Value	The GPU and PCA AGVs have an NPV of €-60’000, the rotating chocks concept has an NPV of €234’307, the FOD AGV has an NPV of €-40’000, the virtual walls concept has an NPV of €464’227, and the fixed cameras concept for technical inspection has an NPV of €813’198. Combining these yields an NPV of €1’351’732 and a score of 3.90.
RAMS	The GPU and PCA AGVs have a RAMS score of 3, the rotating chocks concept has a score of 4, the FOD AGV has a score of 4, the virtual walls concept has a score of 5, and the fixed cameras concept for technical inspection has a score of 4. Combining these yields an average RAMS score of 3.83.
Flexibility	The GPU and PCA AGVs have a flexibility score of 5, the rotating chocks concept has a score of 3, the FOD AGV has a score of 5, the virtual walls concept has a score of 5, and the fixed cameras concept for technical inspection has a score of 4. Combining these yields an average flexibility score of 4.5.
TRL	The GPU and PCA AGVs have a TRL score of 1, the rotating chocks concept has a score of 3, the FOD AGV has a score of 3, the virtual walls concept has a score of 5, and the fixed cameras concept for technical inspection has a score of 4. Combining these yields an average TRL score of 2.83.

Multi-Operation

Net Present Value	The GPU, PCA, technical inspection, and FOD AGVs do not generate any savings, whilst the chocks AGV generates around €5233 savings per year and the cones AGV €13’918. An investment cost per AGV of €500’000 can be assumed, due to the high complexity and requirements such as a robotic arm and storage system. Since some tasks, such as cones and chocks, happen in parallel, 2 AGVs will need to be present on a ramp simultaneously. That said, since the main operational tasks, such as baggage loading and fuelling, are not considered, the AGV can likely service 2 ramps on average. With an investment cost per ramp of €500’000 and €19’151 of savings per year, this results in an NPV of €-287’040 using equation 4.4. This gives a score of 2.80
RAMS	The GPU and PCA AGVs have a RAMS score of 3, the chocks AGV has a score of 2, the FOD AGV has a score of 4, the cones AGV has a score of 3, and the land-based technical inspection has a score of 4. Combining these yields an average RAMS score of 3.17.
Flexibility	The GPU and PCA AGVs have a flexibility score of 5, the chocks AGV concept has a score of 5, the FOD AGV has a score of 5, the cones AGV has a score of 5, and the land-based technical inspection has a score of 5. Combining these yields an average flexibility score of 5.
TRL	The GPU and PCA AGVs have a TRL score of 1, the chocks AGV has a score of 1, the FOD AGV has a score of 3, the cones AGV has a score of 2, and the land-based technical inspection has a score of 3. Combining these yields an average TRL score of 1.83.

C

Model code

This code can also be found on GitHub

```python
import locale
from datetime import datetime
import seaborn as sns
import matplotlib.pyplot as plt
import pandas as pd
import numpy as np
from tqdm import tqdm

locale.setlocale(locale.LC_TIME, 'nld_NLD')
delay_costs = {
    "B733": np.array([0.0, 60.0, 360.0, 1290.0, 5780.0, 15710.0, 29730.0, 39930.0, 53720.0, 71300.0]),
    "B734": np.array([0.0, 70.0, 400.0, 1430.0, 6510.0, 17820.0, 33670.0, 45630.0, 60820.0, 80810.0]),
    "B735": np.array([0.0, 60.0, 330.0, 1170.0, 5200.0, 14120.0, 26740.0, 36240.0, 48490.0, 64570.0]),
    "B738": np.array([0.0, 70.0, 440.0, 1580.0, 7200.0, 19730.0, 37270.0, 50050.0, 66970.0, 88410.0]),
    "B752": np.array([0.0, 80.0, 520.0, 1840.0, 8380.0, 22930.0, 43390.0, 58160.0, 77750.0, 102370.0]),
    "B763": np.array([0.0, 150.0, 880.0, 3130.0, 14510.0, 39380.0, 74480.0, 101690.0, 149510.0, 186320.0]),
    "B744": np.array([0.0, 220.0, 1340.0, 4780.0, 22190.0, 60180.0, 114360.0, 156310.0, 213570.0, 265480.0]),
    "A319": np.array([0.0, 70.0, 410.0, 1310.0, 5960.0, 15860.0, 30310.0, 41560.0, 55230.0, 72720.0]),
    "A320": np.array([0.0, 70.0, 410.0, 1490.0, 6800.0, 18860.0, 35280.0, 47420.0, 63030.0, 82840.0]),
    "A321": np.array([0.0, 80.0, 470.0, 1670.0, 7720.0, 21290.0, 39840.0, 53610.0, 71100.0, 93470.0]),
    "AT43": np.array([0.0, 40.0, 260.0, 520.0, 2160.0, 5730.0, 10940.0, 14510.0, 19200.0, 25310.0]),
    "AT72": np.array([0.0, 40.0, 190.0, 670.0, 2900.0, 7780.0, 14840.0, 20160.0, 27630.0, 37690.0])
}

delay_costs_KLM = {
    "E90": np.array([0.0, 70.0, 410.0, 1310.0, 5960.0, 15860.0, 30310.0, 41560.0, 55230.0, 72720.0]) / 1.34,  # A319 adj.
    "295": np.array([0.0, 70.0, 410.0, 1310.0, 5960.0, 15860.0, 30310.0, 41560.0, 55230.0, 72720.0]) / (134 / 118),  # A319 adj.
    "73W": np.array([0.0, 60.0, 360.0, 1290.0, 5780.0, 15710.0, 29730.0, 39930.0, 53720.0, 71300.0]),  # B733 (old version of 73W)
    "73H": np.array([0.0, 70.0, 440.0, 1580.0, 7200.0, 19730.0, 37270.0, 50050.0, 66970.0, 88410.0]),  # B738 w winglets
    "789": np.array([0.0, 150.0, 880.0, 3130.0, 14510.0, 39380.0, 74480.0, 101690.0, 149510.0, 186320.0]) * (406 / 290),  # B763 adj.
    "E7W": np.array([0.0, 70.0, 410.0, 1310.0, 5960.0, 15860.0, 30310.0, 41560.0, 55230.0, 72720.0]) * (88 / 134),  # A319 adj.
    "332": np.array([0.0, 150.0, 880.0, 3130.0, 14510.0, 39380.0, 74480.0, 101690.0, 149510.0, 186320.0]) * (406 / 290),  # A763 adj.
    "781": np.array([0.0, 150.0, 880.0, 3130.0, 14510.0, 39380.0, 74480.0, 101690.0, 149510.0, 186320.0]) * (440 / 290),  # B763 adj.
    "772": np.array([0.0, 150.0, 880.0, 3130.0, 14510.0, 39380.0, 74480.0, 101690.0, 149510.0, 186320.0]) * (440 / 351),  # B763 adj.
    "73J": np.array([0.0, 70.0, 440.0, 1580.0, 7200.0, 19730.0, 37270.0, 50050.0, 66970.0, 88410.0]),  # B738
```

```
    "77W": np.array([0.0, 220.0, 1340.0, 4780.0, 22190.0, 60180.0, 114360.0, 156310.0, 213570.0, 265480.0]) * (550 / 660),  # B744 adj.
    "333": np.array([0.0, 150.0, 880.0, 3130.0, 14510.0, 39380.0, 74480.0, 101690.0, 149510.0, 186320.0]) * (440 / 351),  # B763 adj.
    "32Q": np.array([0.0, 80.0, 470.0, 1670.0, 7720.0, 21290.0, 39840.0, 53610.0, 71100.0, 93470.0])  # A321
}


def calculate_delay_cost(delay, aircraft_type='73H'):  # TODO: Aircraft types
    """
    Calculates the cost of a delay using a continuous equation. Returns float when given float or int, np.array when given an array
    :param delay: Delay in minutes
    :type delay: float or np.array
    :param aircraft_type: Aircraft type
    :type aircraft_type: str
    :return: cost in euro
    :rtype: float or np.array
    """
    global delay_costs_KLM
    delays = np.array([0, 5, 15, 30, 60, 90, 120, 180, 240, 300])
    costs = delay_costs_KLM[aircraft_type]
    cost = np.interp(delay, delays, costs)
    return cost


def calculate_value(dt_turnaround: float, freq: np.ndarray, delay_values: np.ndarray, verbose: bool = False):
    """
    calculates the value in euro when changing the turnaround time by 'dt' without changing the planned time.
    :param delay_values: numpy array with delay values in minutes that should be considered
    :type delay_values: np.ndarray
    :param verbose: function prints extra information
    :type verbose: bool
    :param dt_turnaround: change in turnaround time in minutes
    :type dt_turnaround: float
    :param freq: list or array with frequencies of delays.
    :type freq: list or array
    :return: cost difference in euro
    :rtype: float
    """

    delay_values = np.array(delay_values)
    freq = np.array(freq)

    d_cost = calculate_delay_cost(delay_values + dt_turnaround) - calculate_delay_cost(delay_values)

    relative_cost = freq * d_cost
    value = sum(relative_cost)

    if verbose:
        print("dt_turnaround", dt_turnaround)
        print("delta␣cost:␣", d_cost)
        print("freq:␣", freq)
        print("relative_cost:␣", relative_cost)
        print("value:␣", value)
    return value


def calculate_value_aircraft_type(dt_turnaround: float, flight_data: pd.DataFrame, verbose: bool = False):
    """
    calculates the value in euro when changing the turnaround time by 'dt' without changing the planned time, specified by aircraft_type.
    :param flight_data: flight data
    :type flight_data: pd.DataFrame
    :param verbose: function prints extra information
    :type verbose: bool
    :param dt_turnaround: change in turnaround time in minutes
```

```
    :type dt_turnaround: float
    :return: cost difference in euro
    :rtype: float
    """
    # print(f'calculating values for aircraft types with dt_turnaround = {dt_turnaround}')

    total_delay_cost = 0
    for row, flight in flight_data.iterrows():
        if not np.isnan(flight['Delay']):
            d_cost = calculate_delay_cost(flight['Delay'] + dt_turnaround, flight['AircraftType']) -
                calculate_delay_cost(flight['Delay'], flight['AircraftType'])
            total_delay_cost += d_cost

    value = total_delay_cost / len(flight_data)

    return value


def calculate_value_list(flight_data: pd.DataFrame, freq_data: np.ndarray, min_value: int, max_value: int
    , margin_list: np.ndarray, verbose=False,
                         plot_deprecated=False, use_aircraft_types=True):
    """
    Calculates the values for different margins in a turnaround process
    :param use_aircraft_types: if calculation should use costs for specific aircraft types. Will increase
         computation time significantly.
    :type use_aircraft_types: bool
    :param flight_data: pd.DataFrame with flight data
    :type flight_data: pd.DataFrame
    :param freq_data: numpy array with frequencies of delays.
    :type freq_data: np.ndarray
    :param min_value: minimum delay value (should be same as for freq_data)
    :type min_value: int
    :param max_value: maximum delay value (should be same as for freq_data)
    :type max_value: int
    :param verbose: function prints extra information
    :type verbose: bool
    :param plot_deprecated: function plots deprecated methods used to get frequencies
    :type plot_deprecated: bool
    :param margin_list: numpy array with margin values in minutes that should be considered
    :type margin_list: np.ndarray
    :return: list of values for different margins
    :rtype: list
    """

    delays_1 = np.arange(min_value, max_value + 1, 1)

    if use_aircraft_types:
        value_list = [calculate_value_aircraft_type(dt_turnaround=-dt, flight_data=flight_data)
                      for dt in tqdm(margin_list, "Generating␣Δcost␣values␣for␣KLM␣data")]
    else:
        value_list = [calculate_value(dt_turnaround=-dt, freq=freq_data, delay_values=delays_1)
                      for dt in tqdm(margin_list, "Generating␣Δcost␣values␣for␣KLM␣data")]

    if verbose:
        delays_5 = np.arange(min_value, max_value + 1, 5)
        freq_raw = [0.000, 0.00467, 0.05140, 0.24766, 0.25701, 0.15421, 0.08879, 0.07009, 0.04206,
                    0.01869, 0.01869, 0.01869, 0.01402, 0.00935, 0.00467, 0.000]
        freq_raw += int((max_value - 60) / 5) * [0]
        freq_raw = np.array(freq_raw)

        # Delay vs. Cost
        costs = [calculate_delay_cost(i) for i in delays_1]
        plt.plot(delays_1, costs)
        plt.suptitle('Cost␣of␣delays␣vs␣Delay␣time')
        plt.title('Based␣on␣literature␣on␣737-800␣data', fontsize=10)
        plt.ylabel('Cost␣[Euro]')
        plt.xlabel('Delay␣[Minutes]')
        plt.grid(True, alpha=0.5)
        plt.show()

        # Frequency vs Delay time
```

```
        if plot_deprecated:
            plt.bar(delays_5, freq_raw * 0.2, width=5, alpha=0.5, label='Raw')
        plt.plot(delays_1, freq_data, label='KLM␣Data')
        plt.legend()
        plt.title('Frequency␣Distribution␣vs␣Delay␣time')
        plt.show()

        # Delay vs Cost * Frequency (relative cost)
        if plot_deprecated:
            plt.bar(delays_5, freq_raw * 0.2 * [calculate_delay_cost(float(i)) for i in delays_5], width
                =5, alpha=0.5, label='Raw')
        plt.plot(delays_1, freq_data * [calculate_delay_cost(i) for i in delays_1], label='KLM␣Data')
        plt.legend()
        plt.title('Relative␣Cost␣vs␣Delay␣time')
        plt.show()

        # Plot value vs margin
        if plot_deprecated:
            value_list_raw = [calculate_value(dt_turnaround=float(-dt), freq=freq_raw, delay_values=
                delays_5)
                              for dt in margin_list]
            plt.plot(margin_list, value_list_raw, alpha=0.5, label='Raw')
        plt.plot(margin_list, value_list, label='KLM␣Data')
        plt.xlabel('Margin␣[Minutes]')
        plt.ylabel("Δ␣Cost␣[Euro]")
        plt.grid(which='both', alpha=0.8)
        plt.legend()
        plt.show()

    return value_list


def load_performance_data(verbose: bool = False, min_value: int = -30, max_value: int = 120, shortened:
    bool = False,
                          reprocess: bool = False, vop: list = None):
    """
    Loads the KLM data and transforms it into a dataframe.
    :param verbose: Function should print extra information
    :param min_value: Minimum delay value, any delays below this value will be ignored
    :param max_value: Maximum delay value, any delays above this value will be ignored
    :param shortened: Function should load shortened dataset
    :param reprocess: Function should reprocess dataset (needed if min_value or max_value is changed)
    :param vop: List of VOPs considered
    :return: pd.DataFrame with data
    """

    perf_data = None
    if not reprocess:
        if verbose:
            print('Loading␣performance␣data␣from␣pickle...')

        try:
            if shortened:
                perf_data = pd.read_pickle('Data/Performance_Data_Processed_2025.pkl')
            else:
                perf_data = pd.read_pickle('Data/Performance_Data_Processed.pkl')
        except FileNotFoundError:
            print('ERROR:␣Pickle␣file␣not␣found!')
            reprocess = True

    if reprocess:
        if verbose:
            print("Processing␣performance␣data␣from␣csv...")
        if shortened:
            perf_data = pd.read_csv('Data/vwHubPerformance_2025.csv')
        else:
            perf_data = pd.read_csv('Data/vwHubPerformance.csv')

        delay_list = np.zeros(len(perf_data))
        omitted_max = 0
        omitted_min = 0
```

```
        unreadable = 0
        for row, flight in tqdm(perf_data.iterrows(), total=len(perf_data)):

            scheduled_time = str(flight['ScheduledDepartureTime'])
            actual_time = str(flight['ActualDepartureTime'])

            if scheduled_time != 'nan':
                scheduled_time = datetime.strptime(scheduled_time, "%d-%b-%Y␣%H:%M")

            if actual_time != 'nan':
                actual_time = datetime.strptime(actual_time, "%d-%b-%Y␣%H:%M")

            if scheduled_time != 'nan' and actual_time != 'nan':
                delay = actual_time - scheduled_time
                minutes = int(delay.seconds / 60 + 1440 * delay.days)

                if minutes > max_value:
                    minutes = np.nan
                    omitted_max += 1
                elif minutes < min_value:
                    minutes = np.nan
                    omitted_min += 1
                delay_list[row] = minutes
            else:
                delay_list[row] = np.nan
                unreadable += 1

        perf_data['Delay'] = delay_list
        if shortened:
            perf_data.to_pickle('Data/Performance_Data_Processed_2025.pkl')
        else:
            perf_data.to_pickle('Data/Performance_Data_Processed.pkl')

        if verbose:
            delay_len = len(perf_data)
            print(f"\nTotal␣delay␣values:␣{delay_len}"
                  f"\n\nDelay␣values␣omitted␣due␣to:␣"
                  f"\nOver␣set␣max:␣{omitted_max}␣({round(omitted_max␣/␣delay_len␣*␣100,␣2)}%)"
                  f"\nUnder␣set␣min:␣{omitted_min}␣({round(omitted_min␣/␣delay_len␣*␣100,␣2)}%)"
                  f"\nUnreadable:␣{unreadable}␣({round(unreadable␣/␣delay_len␣*␣100,␣2)}%)")

    if verbose:
        print('\n', perf_data)

    # Filter on vop or pier
    if vop is not None:
        if type(vop) is list:
            if len(vop[0]) == 1:
                perf_data = perf_data.loc[perf_data['VOP'].str.startswith(tuple(vop))]
                if verbose:
                    print(f'Filtering␣performance␣data␣for␣piers:␣{vop}')
            else:
                perf_data = perf_data.loc[perf_data['VOP'].isin(vop)]
                if verbose:
                    print(f'Filtering␣performance␣data␣for␣VOPs:␣{vop}')
        elif type(vop) is str:
            if len(vop) == 1:
                perf_data = perf_data.loc[perf_data['VOP'].str.startswith(vop)]
                if verbose:
                    print(f'Filtering␣performance␣data␣for␣pier:␣{vop}')
            else:
                perf_data = perf_data.loc[perf_data['VOP'] == vop]
                if verbose:
                    print(f'Filtering␣performance␣data␣for␣VOP:␣{vop}')

    if verbose:
        print(perf_data)

    return perf_data


```

```
def gen_freq_dist(data: pd.DataFrame, min_value: float, max_value: float):
    """
    Generates a np.array with the frequency distribution of delays.
    :param data: pd.dataframe of data
    :param min_value: Minimum delay value in data df
    :param max_value: Maximum delay value in data df
    :return: np.array with frequency distribution of delays
    """
    bins = np.arange(min_value - 0.5, max_value + 1.5, 1)
    freq = np.histogram(data['Delay'], bins=bins, density=True)[0]
    return freq


def plot_delay_boxplot(data, y, vop):
    """
    Plots a boxplot for delay data, spread out on y specified.
    :param vop: VOPs considered in data
    :type vop: list or str
    :param data: pd.dataframe of data
    :type data: pd.DataFrame
    :param y: column name of y (for example, 'AircraftType')
    :type y: str
    :return: -
    """
    ax = sns.boxplot(data, x='Delay', y=y, showfliers=False)
    categories = ax.get_yticklabels()
    for tick, label in enumerate(categories):
        aircraft_type = label.get_text()
        n = len(data[data['AircraftType'] == aircraft_type])
        x_pos = 1.01
        y_pos = tick
        ax.text(x_pos, y_pos, f"N={n}", va='center', transform=ax.get_yaxis_transform())
    plt.subplots_adjust(right=0.85)

    if type(vop) is list:
        if len(vop[0]) == 1:
            plt.title(f"Delays␣for␣different␣Aircraft␣Types␣at␣piers␣{vop}")
        else:
            plt.title(f"Delays␣for␣different␣Aircraft␣Types␣at␣VOPs␣{vop}")
    elif type(vop) is str:
        if len(vop) == 1:
            plt.title(f"Delays␣for␣different␣Aircraft␣Types␣at␣pier␣{vop}")
        else:
            plt.title(f"Delays␣for␣different␣Aircraft␣Types␣at␣VOP␣{vop}")
    else:
        plt.title(f"Delays␣for␣different␣Aircraft␣Types")

    plt.show()


def calculate_value_total(min_delay: int, max_delay: int, reprocess_data: bool, shortened_data: bool, vops: list or str,
                          margin: float, margin_list: list or np.ndarray, verbose: bool, plot_deprecated: bool, use_aircraft_types: bool,
                          investment: float):
    """
    Calculates the total value of a decrease (or cost of increase) in turnaround time
    :param min_delay: Minimum delay value in data to be considered
    :type min_delay: int
    :param max_delay: Maximum delay value in data to be considered
    :type max_delay: int
    :param reprocess_data: Reprocess data
    :type reprocess_data: bool
    :param shortened_data: Use shortened data-set
    :type shortened_data: bool
    :param vops: String or list of VOPs to be considered (like 'B20')
    :type vops: str or list
    :param margin: Amount of margin extra created
    :type margin: float
    :param margin_list: List of margins to be used for plots
    :type margin_list: list or np.ndarray
```

```
    :param verbose: Print extra information
    :type verbose: bool
    :param plot_deprecated: Plot deprecated data from literature
    :type plot_deprecated: bool
    :param use_aircraft_types: if calculation should use costs for specific aircraft types. Will increase computation time significantly.
    :type use_aircraft_types: bool
    :return: Total difference in cost
    :rtype: float
    """
    data_df = load_performance_data(verbose=verbose, min_value=min_delay, max_value=max_delay, shortened=shortened_data,
                                    reprocess=reprocess_data, vop=vops)

    frequencies = gen_freq_dist(data_df, min_value=min_delay, max_value=max_delay)

    if verbose:
        plot_delay_boxplot(data=data_df, y='AircraftType', vop=vops)
        plot_delay_boxplot(data=data_df, y='Pier', vop=vops)

    values = calculate_value_list(flight_data=data_df, freq_data=frequencies, min_value=min_delay, max_value=max_delay, margin_list=margin_list,
                                  verbose=verbose, plot_deprecated=plot_deprecated, use_aircraft_types=use_aircraft_types)
    total_value = round(np.interp(margin, margin_list, values), 4)
    print(f'\nTotal␣value␣for␣a␣margin␣of␣{margin}␣minutes␣({margin␣*␣60}␣seconds)␣is␣{total_value}.␣'
          f'\n(min_value␣=␣{min_delay},␣max_delay␣=␣{max_delay},␣VOP␣=␣{vops}')

    flights_p_year = len(data_df) / 670 * 365
    print(f'{len(data_df)}␣flights␣total␣({flights_p_year}␣flights␣per␣year)')
    print(f'ΔCost␣per␣year␣=␣{flights_p_year␣*␣total_value}')

    vop_count = len(pd.value_counts(data_df['VOP']))
    yearly_savings = flights_p_year * total_value / vop_count
    print(f'ΔCost␣per␣year␣per␣VOP␣=␣{yearly_savings}.␣({vop_count}␣VOPs)')

    years = 15
    r = 0.04
    # investment = int(input(f'\nInput initial investment (in euro) to calculate the corresponding score (assuming {years} years)'))
    discount_constant = (1 - (1 + r)**(-years)) / r
    print(f'discount_constant␣=␣{discount_constant}␣(for␣r␣=␣{r})')
    npv = -investment + (-yearly_savings * discount_constant)
    print(f'npv␣=␣{npv}')
    score = 3 + npv / 250000
    print(f'score␣=␣{score}')
    return total_value


if __name__ == '__main__':
    margins = np.arange(-5, 5, 0.1)
    total_d_cost = calculate_value_total(min_delay=-15, max_delay=180, reprocess_data=False, shortened_data=False,
                                         vops='D', margin=(30) / 60, margin_list=np.arange(-1, 2, 1),
                                         verbose=False, plot_deprecated=False, use_aircraft_types=True, investment=0)
```