D5.4 –

Cost Assessment

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AEON

ADVANCED ENGINE-OFF NAVIGATION

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Abstract

This document outlines the cost benefit analysis for both towing as integrated eTaxi system to determine the viability of these solutions. Initially a qualitative overview of the costs and benefits is given. For towing, an analysis for a peak day at the top 25 airports in Europe is done, showing the maximum potential and the variation of fuel savings for different airports as well as the number of tow vehicles required to tow all ground movements. Next a more detailed analysis is done for both Amsterdam Airport Schiphol and Paris Charles de Gaulle is done by looking at the trade-off between the number of towing vehicles and the potential savings per tow vehicle on that peak day.
Finally, an analysis is done for installing eTaxi devices on aircraft within a fleet of ten European airlines taking into account how the aircraft equipped with these devices can be deployed within an airlines network to optimize the fuel saved on the ground vs. the additional fuel used in the air due to the additional weight.

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1 Introduction

1.1 Purpose of the document

This document outlines the main ideas and core principles of the cost and benefit assessment in AEON. Note that the ideas described in this document are possible solutions in line with the exploratory nature of AEON project and its low TRL level. It aims to explore the benefits and requirements non-engine taxiing at a high level to determine potential opportunities. It is not meant as a financial cost benefit analysis, as there are too many uncertainties. Before towing or autonomous eTaxi is applied, a more specific study should be done for the given airport (for towing) or airline (for eTaxi), where this document can hopefully provide some starting points.

1.2 Intended readership

The intended audience of this report are mainly the AEON Consortium to be used as reference. However, the intended readership also includes:

- the key stakeholders targeted by the solution, in particular ground handlers, airport management, airlines, ATC operators and the industry providing green taxiing solutions, most of which are also represented in the AEON Advisory Board.
- the overall aviation community interested in the document, as it will be publicly available.

1.3 Related documents

This deliverable builds upon or relates to the following documents:

- D1.1 Initial Concept of Operations, providing the concept that has been assessed in the validation activities
- D2.1 Models and Algorithms for Autonomous and Non-autonomous Taxiing Operations
- D2.2 Model for Optimal Allocation of Towing Vehicles, outlining the algorithm used for the tug allocation that obtains time and distance information from the path planning algorithm described in this document.

1.4 Structure of the document

Chapter 1 contains general information about the project and the work done for this deliverable.

Chapter 2 gives a general overview of the costs and benefits that need to be considered for alternative taxi systems.

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Chapter 3 contains an overview of the fuel savings and tow trucks required for implementing towing at the largest European airports, and an analysis based on simulation of decoupling operations.

Chapter 4 contain an overview of implementing an autonomous eTaxi system for the largest European airlines.

Chapter 5 contains the conclusions and recommendations.

1.5 Acronyms and terminology

Term	Definition
A-CDM	Airport collaborative decision making
AIAA	American Institute of Aeronautics and Astronautics
ARN	Stockholm Arlanda Airport
A-SMGCS	Advanced surface movement guidance and control system
ATC	Air Traffic Control
ATH	Athens Airport
AEDT	Aircraft Environmental Design Tool
AMS	Amsterdam Airport Schiphol
APU	Auxiliary Power Unit
BCN	Barcelona Airport
BRU	Brussels Airport
CAPEX	Capital Expenses
CDG	Paris Charles de Gaulle
CPH	Copenhagen Airport
DUB	Dublin Airport
DUS	Dusseldorf Airport
ECDT	Engine Cool Down Time
ESUT	Engine Start Up Time
ETS	Emissions Trading Scheme

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FAA	Federal Aviation Administration
FCO	Leonardo da Vinci–Fiumicino Airport
FRA	Frankfurt International Airport
HEL	Helsinki Airport
ICAO	International Civil Aviation Organisation
IST	Istanbul
JFK	John F Kennedy International Airport
KLM	Royal Dutch Airlines
LIS	Humberto Delgado Airport
LHR	London Heathrow Airport
LGW	London Gatwick Airport
MAD	Madrid Barajas Airport
MUC	Munich Airport
MXP	Milan Malpensa Airport
OAG	Official Airline Guide
OPEX	Operational Expenses
ORY	Paris Orly Airport
OSL	Oslo Airport
PMI	Palma Airport
TXL	Berlin Tegel "Otto Lilienthal" Airport
VIE	Vienna International Airport

2 Cost benefit analysis

In this chapter on overview is given of the different costs and benefits of alternative taxi methods will be described in a qualitative fashion. Focus will be on towing, as this is most potentially interesting solution.

Before an alternative to taxiing with engine thrust can be implemented, the costs must be lower than the benefits. Most costs for engine off taxi operations will generally directly or indirectly be covered by the airline. For operational towing, this can either be a ground handling charge or an increase in landing fees as a result of increased aeronautical cost for the airline. For autonomous eTaxi, most costs and benefits are directly for the airline.

Costs related to airport collaborative decisions making (A-CDM) and advanced surface movement guidance and control system (A-SMGCS) are not considered, as the marginal costs of implementing towing or eTaxi solution on these systems are impossible to quantify.

2.1 Costs

Costs can generally be divided into investment costs and operational costs, also known as capital expenses (CAPEX) and operational expenses (OPEX), where CAPEX are one-time costs and OPEX are recurring. If tow trucks are bought, they are a capital expense, however they could also possibly be rented. In any case, all capital cost will have to be converted to a daily or yearly costs using a depreciation rate.

2.1.1 Infrastructure

Depending on the airport, some changes in airport infrastructure could be required when implementing operational towing of aircraft. These changes involve modifications to stands (such as adding charging facilities), taxiways and service roads and are generally an investment or capital expense which needs to be recovered over a longer period of time. The exact costs of these modifications are very specific to each airport, depending on traffic level, airport layout and local building costs and thus not possible to determine on a higher level in the scope of this project. These costs will lead to an increase in aeronautical costs and thus landing costs, unless covered by government subsidies.

For autonomous eTaxi, no significant modifications to infrastructure are likely to be required. If the taxi speeds do cause congestion and delays, additional taxiways or passing locations might be required.

2.1.2 Aircraft modifications

For towing, the main cause of concern is the additional forces on the nose gear, which could cause issues in time requiring modifications to the wheel gear assembly. For now, it is assumed that aircraft will not need to be modified significantly for towing operations, even though current Airbus aircraft do need an update to their nose wheel steering system for use with the towing vehicle.

For autonomous eTaxi, modifications are required to the aircraft including installation of the system and modification of the auxiliary power unit and the cockpit to allow for control of these systems.

significant modifications are foreseen for the airport. As these modifications are fixed, they have no resale value, and these costs are basically capital expense that will only be recovered while the aircraft is active. No significant modifications are foreseen for the airport.

2.1.3 Equipment

For towing, additional towing vehicles have to be acquired. While this is a capital expense if they are bought, these are mobile assets which could be potentially rented or resold. The resale value is uncertain as the market for towing vehicles could be large or limited. In general, operating the towing vehicles can be assumed to lead to a fixed depreciating cost per day which must be taken into account. As we are looking at a peak day, this day will require vehicles to be used more than the average day and not fully utilized on other days, resulting in a slightly higher depreciation for that day. For example, if a towing vehicle costs 2 million Euro, has a lifespan of 10 years and can be used effectively 250 days per year, the depreciation would be 800 Euro per day. This depreciation needs to be recovered, independent of who does the investment.

The autonomous eTaxi system reduces the need for equipment on the ground, namely the pushback truck. [7]

2.1.4 Staff

For towing staff cost, which include drivers and management staff, are generally seen as an operational expense. Recruiting staff and making staff redundant is not trivial and comes at significant cost in time and money. If towing vehicles would need to be manned all time, this thus significantly increases the cost of operations and can make it uneconomical. Autonomous or remotely controlled towing vehicles would therefore significantly improve the business case. Still the cost of a tug fleet manager would need to be included, but this cost is relatively low, especially for large towing fleet sizes and could possibly be covered by existing staff positions such as pushback controllers. Additionally, there could be an impact on ATC workload requiring extra staff there. Finally training costs, for example for pilots and tug drivers, may also have to be considered.

For autonomous eTaxi no significant impact on staff levels is expected except for the removal of the need for a pushback truck, though additional training for the pilots of equipped will be required. While no tug driver is required, a wing walker will most likely be required instead.

2.1.5 Energy

The towing vehicles require energy to run, which can currently either come from diesel or batteries and might come from hydrogen in the future. This results in a cost per unit of energy needed. For electric vehicles this is next to the investments needed to provide the infrastructure needed for supplying and storing electricity and charging vehicles, mentioned in 2.1.1.

Autonomous eTaxi requires additional power from the APU, which will lead to an increase in fuel consumption of the APU, next to the additional fuel burn in flight due to the increased aircraft weight.

For life cycle costs, the energy costs of building, maintaining and disposing the solutions should also be taken into account, which might be less favourable for battery powered vehicles.

2.1.6 Delay

Implementing engine off operations might lead to extra taxi time, which could lead to increased staff and aircraft depreciation costs. If there is a deviation with respect to a target time indirect costs for potential passenger delay occur. As these delays are likely limited, in the order of minutes per operation, these are not likely to impact the financial business case. They might still cause operational complexities, such as congestionThis should be evaluated at each airport.

For towing, acceleration will be a bit less, but the maximum speed is assumed to be similar to engine on taxiing, so the effect on congestion should be limited. For autonomous eTaxi, this is very much dependant on the final performance of the system and the available traction and power, especially for systems using the nose wheel. [8] . Operationally, additional time should be taken into account in the taxi times used to calculate the required time between target off block time (TOBT) and target take off time (TTOT).

2.2 Benefits

The main direct financial benefits of engine off towing are going to be in fuel savings for the airline as will be discussed below, while the airport might have some indirect benefit due to lower environmental impact.

2.2.1 Fuel

The main source of cost savings is by reducing the fuel consumed by the main engines during taxi. With current towing vehicles, the Auxiliary Power Unit (APU) will still need to be running, which can reduce the fuel savings slightly. If future versions could supply power, preconditioned air and even air starter units for the engines, APU and thus fuel usage could be reduced further.

For autonomous eTaxi, also the main engines will use less fuel, but the APU will need to run at higher power to provide the electric power for the motors. As the weight of the aircraft will increase due to the motors and related modification, the fuel burn will increase during flight.

2.2.2 Maintenance

Maintenance costs are difficult to quantify but will most likely have a net benefit. On the one hand less usage of engines should mean less maintenance. The main brakes will most likely be applied less leading to less wear of the brakes as speed can be controlled much more easily by the electric motor or tug than it can be by applying engine thrust. These are costs that will have to be monitored but are not expected to have a significant impact on the business case.

For towing wear of the nose wheel gear could be increased due to the additional forces while towing, while.

For autonomous eTaxi additionally the wheels assembly will require extra maintenance, as well as the APU, which will need to provide more power. [7]

2.2.3 Environment

Most environmental effects will be directly related to a reduction in fuel consumption. Reduction and emissions will generally not lead to direct financial benefits but in some cases might mean that more flight can be accommodated within environmental limits. Emissions, such as particulate matter and NOx, might have a local impact with indirect financial consequences. Most environmental effects will be directly related to the fuel consumption.

For towing, there will be an overall reduction in fuel consumptions and emissions. While diesel or diesel-electric powered trucks will burn fuel and cause some emissions, this is much less than what the aircraft engines would use. Emissions of partial or fully electric trucks will not be on site and depend on the source of the electricity.

For autonomous eTaxi, fuel burn and particularly NOx production will increase in flight due to the additional weight. The overall benefit is thus highly dependent on taxi time vs. flight distance.

The detailed study of each technique on environmental impact is not in the scope of this project. However, the work related in “Camilleri, Robert & Batra, Aman. (2021). Assessing the environmental impact of aircraft taxiing technologies.” gives an initial overview.

2.3 Accounting

As for towing the costs are borne on an airport level, either directly by the airport itself or a ground handler, and the benefits are mainly for the airline, mostly in a reduction in fuel consumption, some settlement will have to take place. The two most logical ways to charge these costs to the airlines are the landing charge and ground handlings costs.

If the landing charge would be increased to cover the costs, this would de facto mean that all outbound and possibly inbound aircraft will be towed by default. In case there are not enough towing vehicles present, a rebate could take place to compensate the airline. This model fits best with a single operator for all towing vehicles and would lead to the higher utilization of towing vehicles.

If an additional charge would take place per towing operation, this would leave it much more to the airline to decide whether they are towed or not, and by who if multiple companies supply this service. This model would allow towing take place by the ground handler but coordinating between the ground handlers would be much more complex. Also, overall utilization could be significantly lower. This could lower the adoption rate and lead to an higher average cost per user.

If the cost of towing increases for airspace users, the adoption rate would decrease.

For autonomous eTaxi, all costs and benefits are for the airline. Handling charges will be lower due to not requiring a tow truck for push back. To incentivise the airline to implement this, an option could be to give aircraft equipped with autonomous eTaxi a reduction in landing charges.

3 Cost benefit analysis for towing operations

Cost and benefit analysis for towing operations is two-fold. On one hand, fuel costs and environmental impact of using towing vehicles in taxiing operations are evaluated. On the other hand, system performance of introducing new tasks for decoupling towing vehicles in outbound process and allocating new spaces is analysed since the indirect costs and benefits of such changes in airport infrastructure are highly impacted by the way the system is designed. Thus, in Section 3.1, fuel cost and environmental impact of using towing vehicles in taxiing operations are analysed. In Section 3.2, system performance regarding decoupling of towing vehicles is evaluated.

3.1 Analysis of costs and environmental benefits for towing operations

As there is much uncertainty with respect to actual costs of towing vehicles, aircraft modifications and the (highly volatile) cost of fuel, these costs will be shown as number of towing vehicles or eTaxi equipped aircraft and the benefits in fuel per peak day. A current rough indication for the price of fuel is $1.00 per kg, excluding tax [6]. The estimated current cost for an operational towing vehicle for medium sized aircraft is around $2 million.

3.1.1 Methodology

It is expected that implementation of towing at larger airports is more likely to produce larger fuel savings, due to longer taxi times and traffic being more evenly distributed through the day. Also, medium sized jets are the most likely candidates for towing, as most of the flights are performed by these and these are used throughout the day, where large and long-range aircraft are operated mostly during the morning and early evening. Regional airports with a single runway are not very likely to be able to utilize towing vehicles effectively as taxi out times are not going to significantly exceed the four minutes warm up time or the two minutes cool down time and the traffic levels limit utilization. Off course single engine taxying and autonomous eTaxi could still be feasible.

The data use for assessing the utilization of towing vehicles is:

- A peak day extracted from a global Official Airline Guide (OAG) timetable for 2018 [1]
- Taxi times for 2018 published by Eurocontrol [2]
- ICAO Fuel and emissions data for aircraft extracted from the Aviation Environmental Design Tool (AEDT) [3][4]
- Estimates for APU fuel consumption published by ICAO [5]

As we are doing a high-level analysis, four different aircraft types are modelled with respect to fuel consumption, values of which are given in table 1. These types then represent 73% of the total number of flights in the peakday flight schedule. The size indicates the equivalent type of towing vehicle, which are assumed to not be cross compatible. For example a heavy truck cannot tow a medium aircraft, due to the size (especially height) of the vehicle.

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The representative aircraft types are:

- The Embraer 190 represents all Embraer E-jets and Airbus A220's
- The Airbus A320-200 represents all A320 family aircraft, including the NEO.
- The Boeing 737-800 represents all B737 aircraft including the Max.
- The Airbus A350-900 represents al twin engine wide body aircraft.
- All regional and four engine widebody aircraft were not considered.

Table 1: Fuel consumption and emissions values for representative aircraft types or normal taxi and single engine taxi (SET)

ID	Size	Fuel flow normal [kg/s]	CO normal [g/kg]	HC normal [g/kg]	NOx normal [g/kg]	Fuel flow SET [kg/s]	CO SET [g/kg]	HC SET [g/kg]	NOx SET [g/kg]
E190	Small	0.176	41.73	4.02	3.69	0.132	22.88	2.06	5.82
A320	Medium	0.204	32.07	1.92	4.22	0.153	17.66	0.99	6.54
B738	Medium	0.22	29.39	1.54	4.36	0.165	16.11	0.80	6.73
A350	Heavy	0.582	21.46	1.03	4.41	0.437	11.32	0.52	7.77

Figure 1 illustrates how this data was combined into a table of fuel and emissions values changed per aircraft type and airport.

To get an upper bound on what the savings could be, the workflow in figure 2 shows how this was combined in a global analysis, determining the maximum possible savings that could be achieved and the number of tow trucks required to achieve this. It should be noted that this estimate is somewhat unrealistic as some tow trucks at some airport would not be utilized enough to make any economic or environmental sense.

In the final analysis, performed for Amsterdam Airport Schiphol and Paris Charles de Gaulle, an optimal assignment model was used, which then plans and assigns tow trucks to flights. An important parameter is that each additional tow truck used throughout the day must offset a minimum amount of fuel. Figure 3 illustrates the workflow for the optimization.

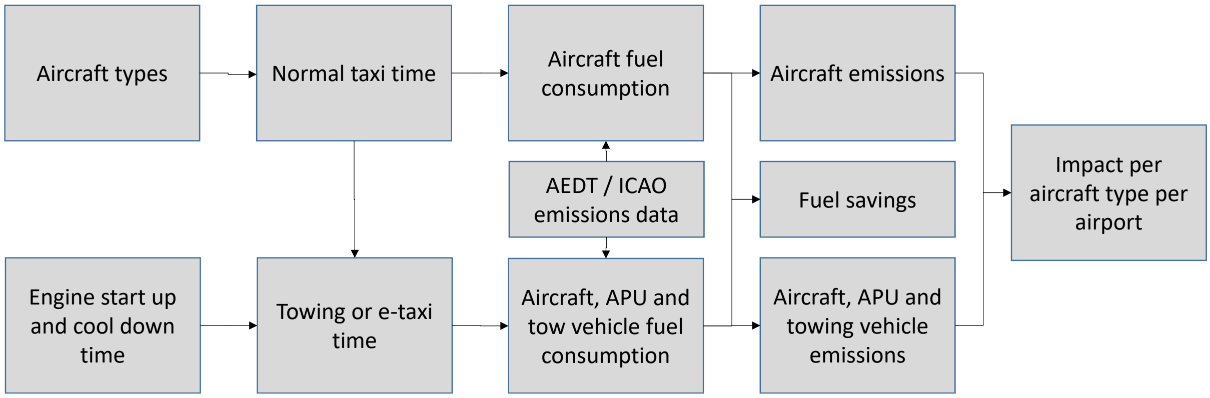

Figure 1: Calculation for determining impact numbers per aircraft type and airport

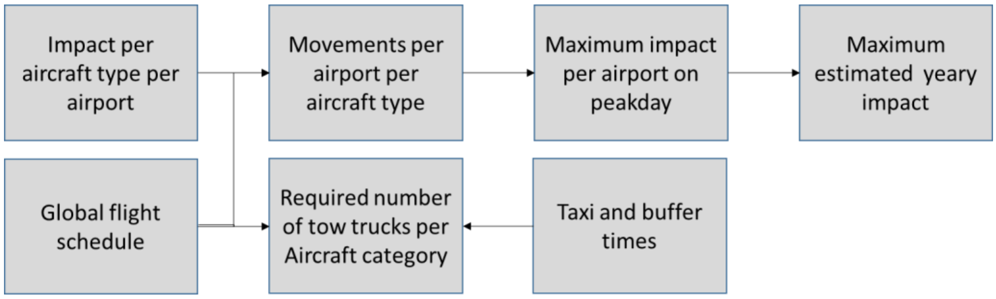

Figure 2: Calculating maximum total impact of introducing towing

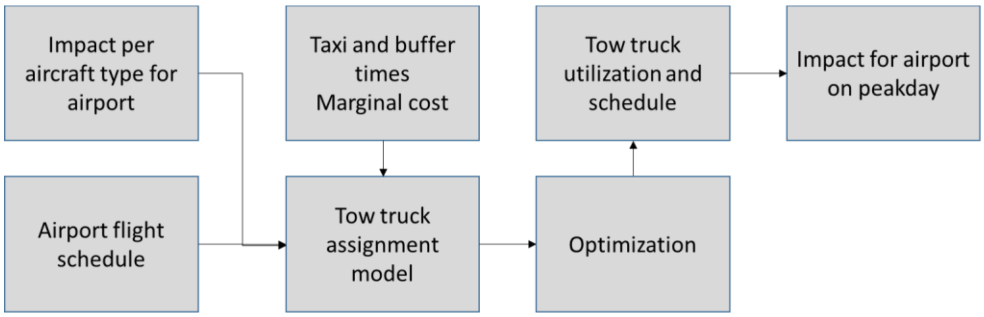

Figure 3: Optimizing Tow truck assignment workflow

Also for single engine taxiing (SET) results are included. The savings for SET are calculates using the same procedure as towing, except while towing one engine is assumed to be running at a fuel flow of 1.5 times idle, resulting in a 75% of fuel flow for all engines taxiing. Emissions values are interpolated between the values for idle and approach, as a higher fuel flow will lead to higher combustion temperatures and thus different emissions.

3.1.2 Results for full deployment

Table 2 shows the calculated savings on fuel consumption on a peak day at 25 European airports and the number of tow trucks required for towing all these flight movements, assuming taxi time plus 20 minutes return and buffer time required per movement and calculating the number of simultaneous movements per 5-minute block. The results are illustrated in figures 4 and 8. Small trucks are used to tow regional jets, such as the Embraer 190 and the Airbus 220 (the former Bombardier C-Series). Medium trucks tow Boeing 737's and Airbus A320's. Finally, Heavy trucks tow all twin engine wide bodies. Currently, four engine wide bodies are not taken into account.

As can be seen, Amsterdam and Paris CDG have the highest number of tow trucks required and close to the highest total fuel savings of all airports in the table. When it comes to savings per tow truck, Istanbul and London Heathrow stand out, mostly due to the increased taxi time due to (departure) delays but for Heathrow also the relatively high percentage of heavy aircraft. A reasonable initial lower value, dependant on fuel price and the cost of operating a towing vehicle, would be in the order of 1000 kg of fuel savings per towing vehicle per day, with $1.00 per kg of fuel, this would allow $1000 per day of costs per towing vehicles. This would include 13 of the 25 airports in table 1.

Table 2: Number of tow trucks required and maximum potential daily savings for top 25 airports in Europe

Airport	Taxi Out (min)	Taxi In (min)	Small	Medium	Large	All	Fuel saving SET per peakday (kg)	Fuel saving towing per peakday (kg)	Fuel savings per truck (kg)
AMS	8.0	13.9	22	42	16	80	45452	118505	1481
CDG	9.5	16.3	17	43	19	79	49909	132588	1678
FRA	9.2	14.3	10	52	16	78	43830	124879	1601
MAD	8.9	18.2	8	41	14	63	40386	118872	1887
FCO	9.1	17.3	6	47	8	61	36295	106388	1744
LHR	8.6	22.3	2	39	24	65	59924	173813	2674
MUC	5.8	13.1	10	42	8	60	23063	65611	1094
BCN	5.4	18.1	2	45	8	55	32008	95828	1742
LGW	7.1	21.4	4	40	7	51	34516	98754	1936
BRU	5.6	11.8	4	39	6	49	12088	32050	654
ZRH	5.4	12.8	10	27	9	46	14681	40933	890
DUB	7.6	18.3	11	26	6	43	20437	61226	1424
PMI	5.5	12.7	4	36	1	41	12162	34968	853
IST	9.6	19.9	0	27	12	39	41494	107413	2754
ATH	6.3	13.7	3	32	3	38	10335	30207	795
DUS	5.1	12.2	5	28	4	37	10903	30818	833
LIS	5.1	13.7	8	26	3	37	13319	34982	945
ORY	5.8	11.2	2	32	3	37	13754	32281	872

HEL	4.9	10.4	4	27	5	36	6834	17830	495
OSL	4.4	10.3	2	29	4	35	10233	27333	781
CPH	5.9	13.3	0	29	6	35	14764	42428	1212
MXP	6.0	13.5	6	23	5	34	14933	40922	1204
TXL	5.3	10.4	3	29	2	34	10268	28847	848
VIE	7.3	11.8	3	29	3	35	12528	34063	973
ARN	6.5	11.3	1	27	4	32	11452	31743	992
Total			**147**	**857**	**196**	**1200**	**595568**	**1663281**	**1386**

3.1.3 Mathematical formulation of the optimum assignment model

The mathematical model is used to determine the trade-off between the number of tow trucks deployed and the fuel saving, by using a minimum marginal cost per towing vehicle in kilograms of fuel per day.

3.1.3.1 Variables

z_F : Total fuel savings

z_V : Costs per towing vehicle per day in kilograms of fuel

y_V : Vehicle v is used (binary)

$x_{o,v}$: Operation o is towed by vehicle v (binary)

3.1.3.2 Sets

O: Operations (arrivals and departures)

O_v: Operations compatible with towing vehicle v

V: Towing vehicles v

V_o: Towing vehicles compatible with operation o

T_O: Time intervals where a towing operation starts

3.1.3.3 Parameters

C_V: Marginal cost per vehicle

$C_{F,o}$: Fuel saving per operation (if towed)

3.1.3.4 Objectives

Maximize $Z = z_F - z_V$

$$z_V = \sum_{v \in V} C_V y_V$$

$$z_F = \sum_{v \in V} \sum_{o \in O_v} C_{F,o} x_{o,v}$$

The objective Z of the model consists of two parts. Z_V is the marginal cost of deploying a vehicle per day, in equivalent kilograms of fuel and Z_F is the total amount of fuel saving. Essentially an extra vehicle will only be deployed if the extra fuel savings outweigh the cost of that vehicle.

3.1.3.5 Constraints

The first constraint allows each flight to be only towed by one, to avoid multiplying the benefits.

$$\sum_{v \in V_o} x_{o,v} \leq 1, o \in O$$

The second constraint ensures that each towing vehicle can only tow one aircraft at a time, where the time also takes into account repositioning and an uncertainty buffer.

$$\sum_{o \in O_{v,t}} x_{o,v} - y_V \leq 0, v \in V, t \in T_O$$

3.1.4 Results Amsterdam Airport Schiphol

Table 3 shows the savings in fuel per movement using single engine taxi and table 4 shows the savings in fuel per movement that is being towed at AMS. The peakday flight schedule has a total of 629 departures, the flights thus representing 93%. Savings in fuel are about 3.5-4 times higher for towing than using single engine taxiing. Results for CO and HC are about 1.5-2 times higher and NOx actually shows an increase for single engine taxiing, due to the higher thrust setting of the running engine. It is assumed that during taxi in engines will remain running for 2 minutes for starting the APU and engine cool down, while engines are assumed to be running for 4 minutes on taxi out for engine warm up, resulting in saving on idle engine fuel consumption for approximately 6 minutes on taxi in and almost 10 minutes on taxi out. It should be noted that average values for average taxi times are used, and actual taxi times may significantly vary dependant on the runways in use.

Table 3: Savings per aircraft type per single engine taxi operation at AMS

Type	Size	Peak day departures	Fuel savings per taxi in (kg)	Fuel savings taxi per out (kg)	CO2 taxi in (kg)	CO2 taxi out (kg)	CO taxi in (kg)	CO taxi out (kg)	HC taxi in (kg)	HC taxi out (kg)	NOx taxi in (kg)	NOx taxi out (kg)
E190	Small	133	18	29	58	91	1.81	2.82	0.18	0.28	-0.05	-0.08
B737	Med.	193	23	36	73	113	1.59	2.48	0.09	0.14	-0.06	-0.10
A320	Med.	156	21	33	67	105	1.60	2.50	0.10	0.16	-0.06	-0.09
A350	Heavy	104	61	95	192	300	3.15	4.92	0.16	0.24	-0.34	-0.54

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Table 4: Savings per aircraft type per towing operation at AMS

Type	Size	Peak day departures	Fuel savings per taxi in (kg)	Fuel savings taxi per out (kg)	CO2 taxi in (kg)	CO2 taxi out (kg)	CO taxi in (kg)	CO taxi out (kg)	HC taxi in (kg)	HC taxi out (kg)	NOx taxi in (kg)	NOx taxi out (kg)
E190	Small	133	64	107	201	339	3.07	5.23	0.30	0.50	0.27	0.46
B737	Med.	193	82	138	259	438	2.70	4.60	0.14	0.24	0.40	0.68
A320	Med.	156	75	127	238	402	2.73	4.66	0.16	0.28	0.36	0.61
A350	Heavy	104	220	372	694	1174	5.21	8.89	0.25	0.43	1.07	1.83

For Amsterdam, an analysis was done using the same flight schedule as used in section 3.2. Figure 4 shows the number of taxi movements at each time and thus indicates the requirement for towing vehicles throughout the day, which can be seen to be quite variable. While many vehicles are required for the morning and afternoon peaks, during other times fewer are required. One cause for this is that Amsterdam has a traffic flow with clear inbound and outbound peaks and variable runway configurations for the hub and spoke operation of KLM and partner airlines.

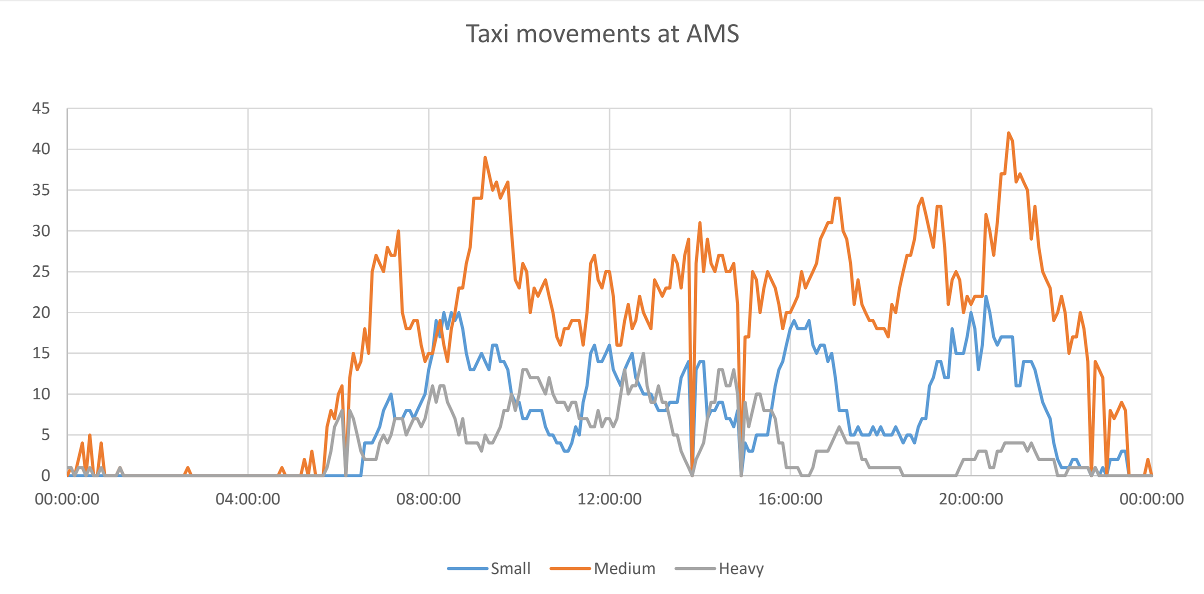

Figure 4: Simultaneous taxi movements throughout the day at AMS

Figure 5 shows how the deployed number of trucks per size varies with the marginal cost in fuel per truck. While for medium and heavy, the full number of trucks stay fairly constant to a value of about 1000 kg per fuel per day, it drops much earlier for the smaller tow trucks, which apparently are used much less effective throughout the day if all regional aircraft are being towed.

Figure 6 shows the effect of deploying a number of trucks on the total fuel savings per truck type. Towing medium sized aircraft, such as the Airbus A320 and Boeing 737 clearly has the highest total impact, but also requires the largest number of trucks. Heavy aircraft require many fewer trucks while still providing relatively large overall savings. The fuel savings for small trucks is relatively small and reducing the number of trucks does not reduce the fuel savings as significantly as with the medium and heavy trucks.

Figure 7 finally shows the average savings per truck as a function of the number of trucks. Heavy trucks clearly provide more savings per truck than medium, however the savings per small truck are clearly the lowest. While heavy trucks are likely more expensive than medium trucks and small trucks are less expensive still, staff costs per truck, especially if the trucks need to be manned, will not vary by much at all. Small trucks would thus be the least cost effective to deploy at Amsterdam.

For heavy and medium trucks, towing all movements seems to be effective enough with an average fuel saving of 1563 kg per medium truck and 2672 kg per heavy truck on a peak day. For small trucks towing all movements would lead to 956 kg of savings per truck, which seems to be more marginal. For the medium and heavy trucks, reducing the number of trucks by one would lead to a de crease in fuel saved, due to fewer aircraft being towed, of more than 1000kg. For small trucks this decrease per truck due to fewer aircraft being towed is only 500kg.

For Amsterdam an estimate of the appropriate fleet size, assuming a 1000 kg marginal fuel saving per towing vehicle in figure 5, would be 15 heavy trucks and 42 medium trucks, able to tow all movements. Potentially around 10 of the small trucks could be deployed, accepting that not all regional aircraft movements can be towed.

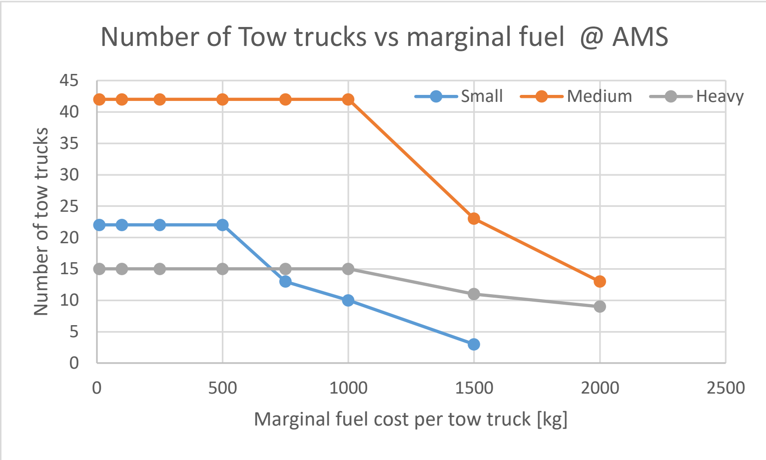

Figure 5: Number of trucks deployed vs. marginal fuel cost per truck on a peak day @ AMS

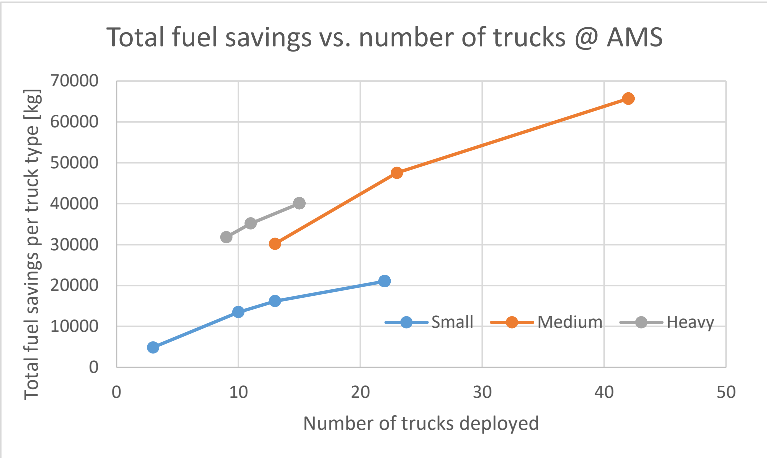

Figure 6: Total fuel savings vs. number of trucks deployed on a peak day @ AMS

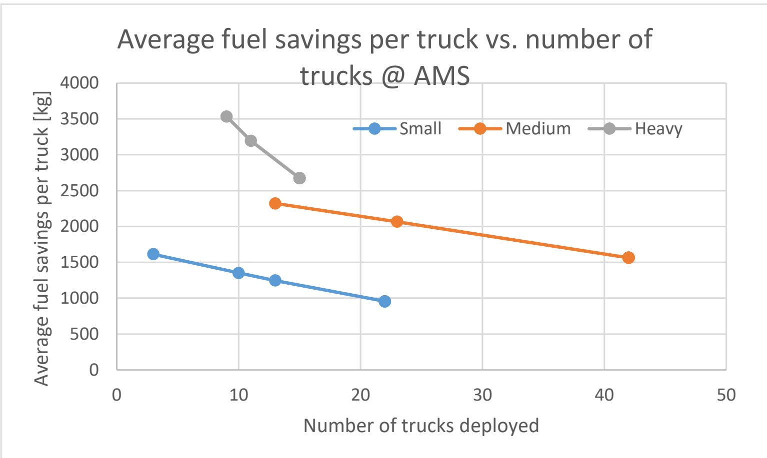

Figure 7: Average fuel saving per truck vs. number of trucks deployed on a peak day @ AMS

3.1.5 Results Paris Charles de Gaulle

Table 5 shows the savings in fuel per operation per single engine taxi operation and table 6 shows the savings in fuel per movement that is being towed at CDG. The peakday flight schedule has a total of 578 departures, the flights thus representing 91.9%. Results for fuel are about 4 times higher for towing than for single engine, where results for CO and HC are about twice as high. NOx actually increases for single engine taxi due to the higher thrust setting of the operating engine. It is assumed that during taxi in engines will remain running for 2 minutes, while engines will all be running for 4 minutes on taxi out, resulting in saving on idle engine fuel consumption for approximately 7.5 minutes on taxi in and almost 12.3 minutes on taxi out.

Table 5: Savings per aircraft type per single engine taxi operation at CDG

Type	Size	Peak day departures	Fuel savings per taxi in (kg)	Fuel savings taxi per out (kg)	CO2 taxi in (kg)	CO2 taxi out (kg)	CO taxi in (kg)	CO taxi out (kg)	HC taxi in (kg)	HC taxi out (kg)	NOx taxi in (kg)	NOx taxi out (kg)
E190	Small	65	20	35	62	111	1.94	3.46	0.20	0.35	-0.05	-0.09
B737	Med.	43	25	44	78	139	1.71	3.05	0.09	0.17	-0.07	-0.12
A320	Med.	328	23	41	72	129	1.72	3.07	0.11	0.19	-0.06	-0.11
A350	Heavy	95	65	116	206	368	3.39	6.04	0.17	0.30	-0.37	-0.66

Table 6: Savings per aircraft type per towing operation at CDG

Type	Size	Peak day departures	Fuel savings per taxi in (kg)	Fuel savings taxi per out (kg)	CO2 taxi in (kg)	CO2 taxi out (kg)	CO taxi in (kg)	CO taxi out (kg)	HC taxi in (kg)	HC taxi out (kg)	NOx taxi in (kg)	NOx taxi out (kg)
E190	Small	65	77	129	244	408	3.74	6.32	0.36	0.61	0.33	0.56
B737	Med.	43	99	167	314	528	3.29	5.56	0.17	0.29	0.49	0.83
A320	Med.	328	91	153	289	484	3.33	5.63	0.20	0.34	0.44	0.74
A350	Heavy	95	267	448	843	1417	6.36	10.8	0.31	0.52	1.31	2.21

Compared to Amsterdam, Paris CDG has a traffic structure which is more constant throughout the day, which is mostly due to the 2 by 2 runway configuration leading to very limited trade-off between the maximum arrival and departure capacity. This also means that taxi movements are a bit more constant throughout the day, as shown in figure 8.

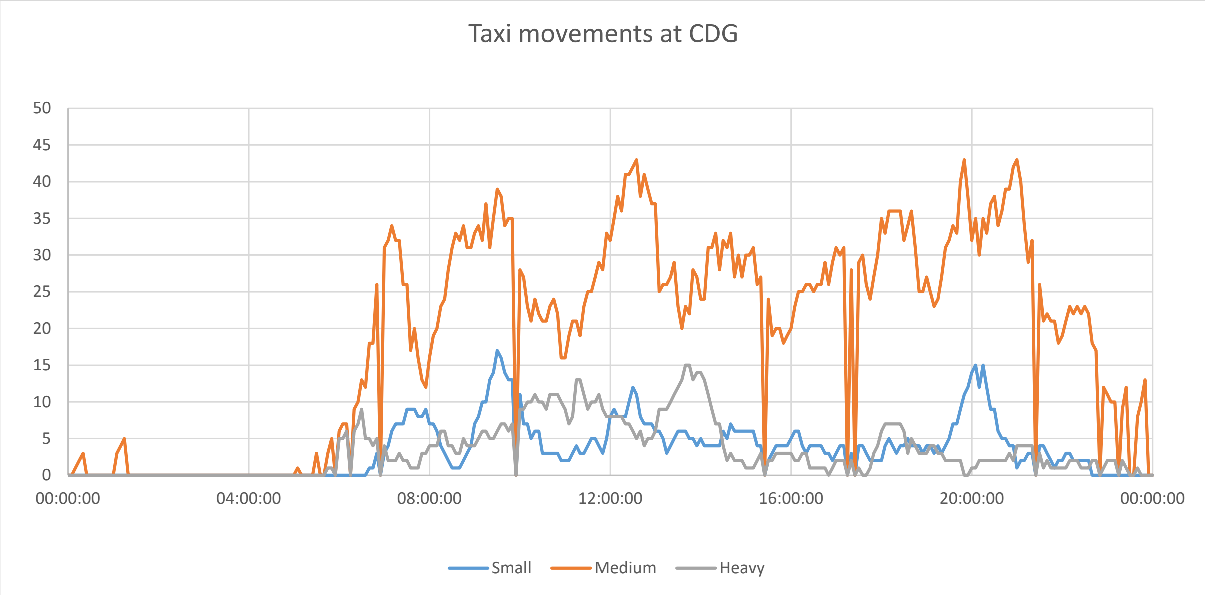

Figure 8: simultaneous taxi movements throughout the day at CDG

Figure 9 shows how the deployed number of trucks per size varies with the marginal cost in fuel per truck. While for medium and heavy, the full number of trucks stay fairly constant to a value of about 1000 kg per fuel per day, it drops much earlier for the smaller tow trucks, which are used much less effective throughout the day if all regional aircraft are being towed. Compared to Amsterdam, especially the medium trucks seem to be utilized more effectively and only drop off after 1500 kg of fuel per truck on the peak-day.

Figure 10 shows how the total fuel savings per truck vary with the number of trucks deployed. Heavy and medium trucks give the highest overall fuel savings, while smaller trucks do not seem highly effective in comparison.

Figure 11 shows that the heavy and medium trucks will be much easier to deploy from a cost-benefit perspective than the small trucks, even if these are likely to be less expensive to build and/or purchase, while the medium and heavy trucks are comparable. Of course, also here the need for a dedicated driver per towing vehicle would make the business case significantly more difficult.

For Paris CDG, the business case looks even a bit stronger than for AMS for the heavy and medium trucks. For large trucks, the average saving is 3209 kg of fuel per vehicle, for medium trucks 2075 kg per vehicle and for small trucks it is only 934 kg per vehicle. The marginal fuel savings for the last truck are at least 1500 kg for the medium, 1000 kg for the heavy but only between 100-250 for the small trucks.

For CDG a reasonable fleet size would be 15 heavy trucks and 43 medium trucks, which would be able to tow al movements. Additionally, only around 6 small trucks could be deployed which would only move a limited number of regional aircraft movements.

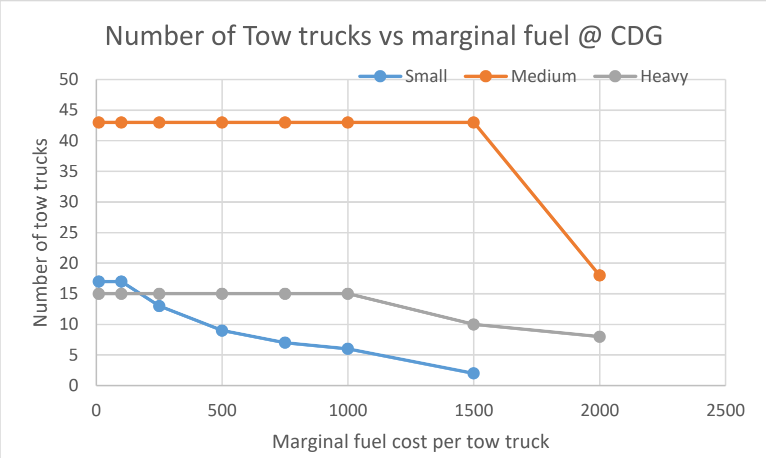

Figure 9: Number of trucks deployed vs. marginal fuel cost per truck on a peak day @ CDG

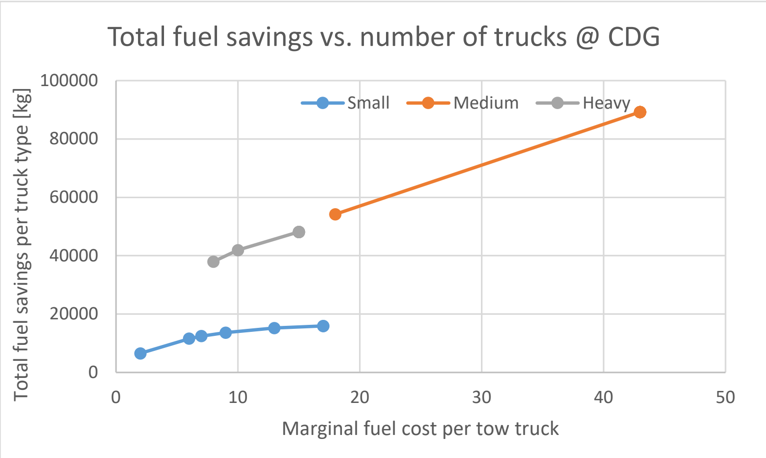

Figure 10: Total fuel savings vs. number of trucks deployed on a peak day @ CDG

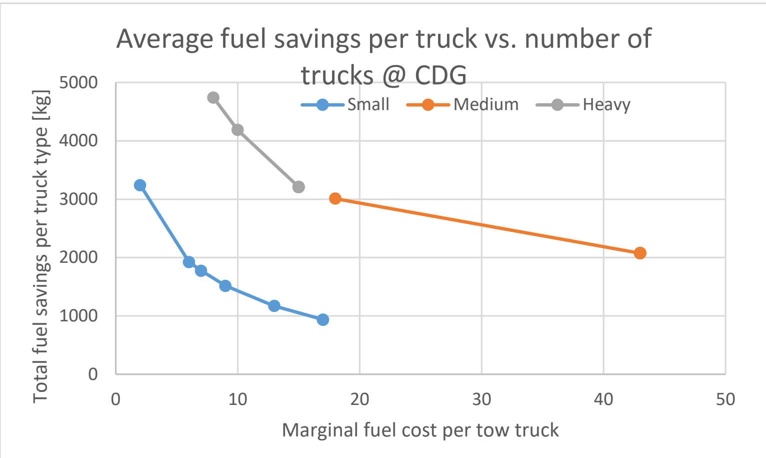

Figure 11: Average fuel saving per truck vs. number of trucks deployed on a peak day @ CDG

3.1.6 Sensitivity analysis for towing

Two main uncertainties regarding the towing of aircraft remain, next to the operating costs of the tow truck and the cost of fuel. These are the scheduled time needed between towing two aircraft and the time needed for the engines to be running before take-off and after landing.

The required buffer time has two components. The first component is the time for the tow truck to reposition from one flight to the next. The other is robustness of the schedule with respect to delays. In the conducted study, the buffer was assumed to be 20 minutes, however this might not be enough for the larger airports and could be lower for the smaller ones. Figures 12 and 13 show the impact on the Malpensa (MXP) case assuming a 500 kg marginal fuel requirement for each truck. More tow trucks are needed, while the savings are only slightly impacted when the buffer time increases. More research should be done to estimate appropriate buffer times and rescheduling in case of delays. A complication with this is that fuel for taxi out needs to be accounted for in flight planning, so last-minute changes could have a significant impact.

Another uncertainty is what the applied Engine Start Up Time (ESUT) and Engine Cool Down Time (ECDT) times are that will be used in reality. If engines are not warmed up enough before take-off or cooled down after landing, this can result in increased wear and thus maintenance. For the analysis and ESUT of 4 minutes and ECDT of 2 minutes was assumed. Figure 14 shows, assuming a 500 kg marginal fuel requirement, that an increase of the ESUT (and increasing the ECDT by the same amount of time) reduces the effectiveness of towing and significantly reduces the total fuel savings, as shown in figure 15.

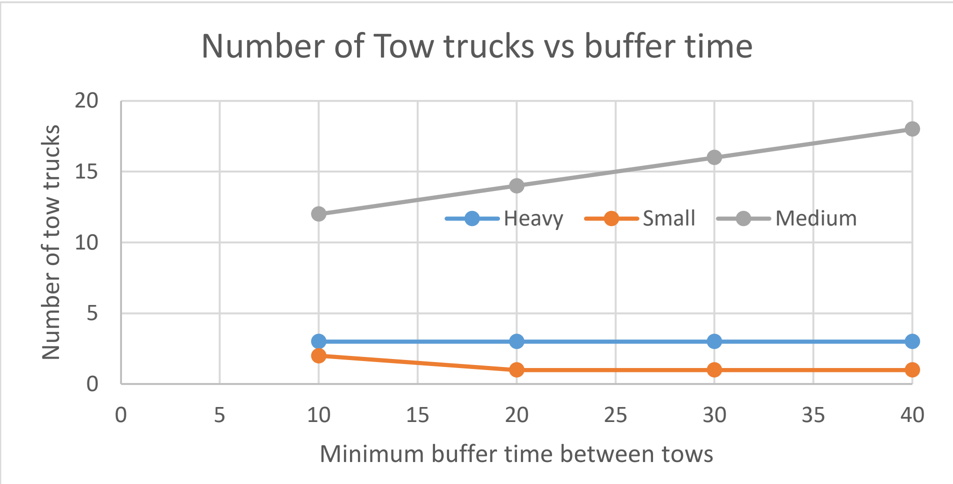

Figure 12: Impact of buffer time on number of tow trucks required

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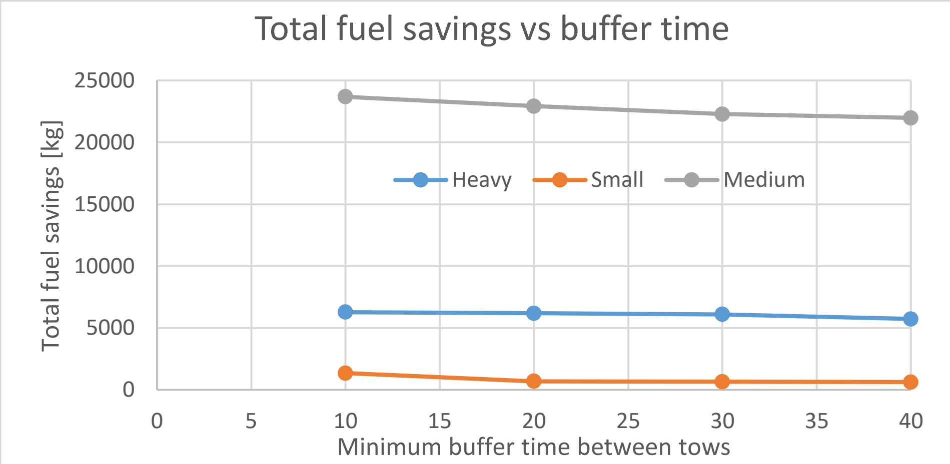

Figure 13: Impact of buffer time on total fuel savings

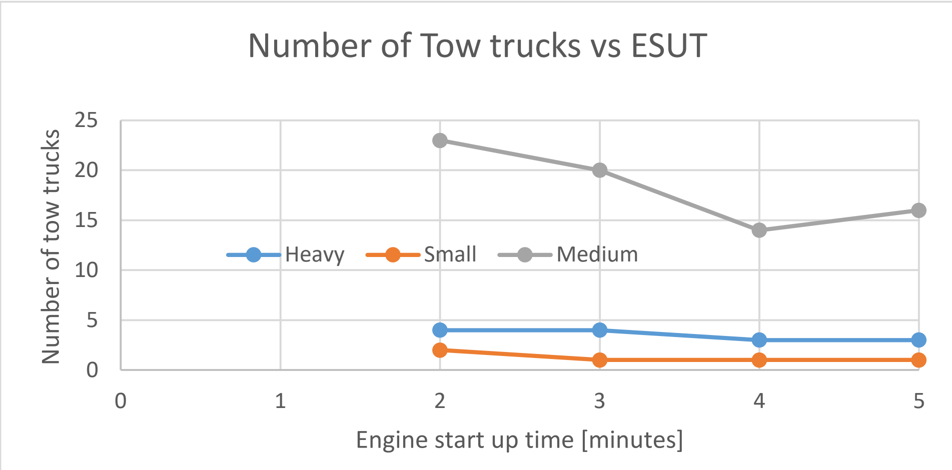

Figure 14: Impact of engine start up time on number of tow trucks deployed

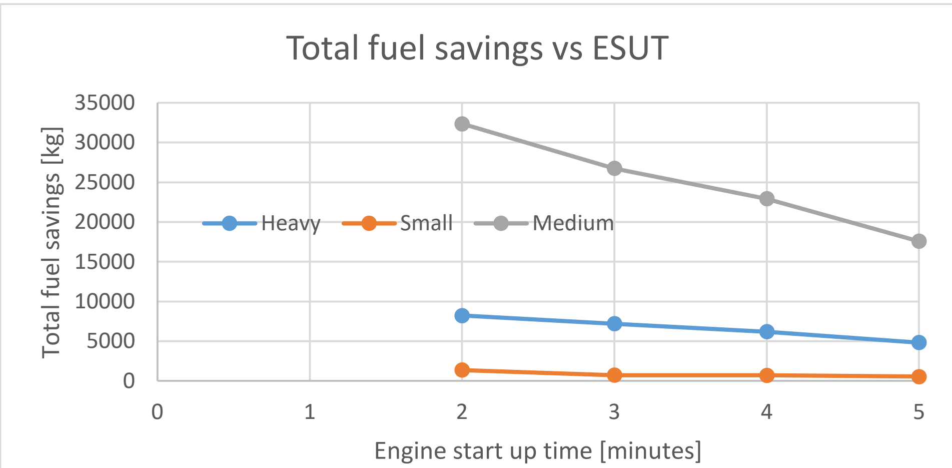

Figure 15: Impact of engine start up time on number of tow trucks deployed

3.2 System performance analysis related to decoupling operations of towing vehicles

In this section required changes in airport infrastructure and how the design of new infrastructure can have impact on (1) reducing or increasing queue sizes or waiting times of aircraft at the airport before take-off, and on (2) utilization ratio. Various scenarios are evaluated.

3.2.1 Content and Scope

If towing vehicles or taxibots are to be used for taxiing operations then there would be a need to allocate spaces for decoupling operations at an airport, preferably close to the runway for outbound taxiing. This also brings the risk of increasing aircraft queue length in front of decoupling locations during peak days or hours. In these cases, other ground operations could be negatively affected due to the limited space at the airport. Deciding on the number of decoupling points and their locations before adopting taxiing systems plays a critical role in avoiding excessive queue sizes and delays in takeoff as well as low utilization.

In this study, we aim to analyze the effects of different number of decoupling locations on queue sizes, waiting times and utilization for various scenarios.

Long term behaviors of queues can be predicted using derivations from Queueing Theory if arrival-service rates and distributions satisfy certain stochastic conditions. On the other hand, there are many cases where these conditions are not met. In these cases, after a high number of simulations of discrete events queue statistics can be computed. By any discrete event we mean arrival of an aircraft at a queue, and release of it after waiting in front of the servers, being serviced, entering other queues and servers, …, etc.

We employ both solution methodologies, “simulation” and “queueing theory”, when applicable. For the cases when stochastic conditions are not satisfied, we use “simulation" methodology.

Queueing models can be seen in practice in many forms such as single queues and multiple parallel servers like in a bank or as sequential queues that must be visited one after another by the arriving entity.

Although we mainly focus on single and multiple parallel decoupling locations assuming that these locations can be reached without any obstacle, we also add a few simulation scenarios with sequential queues. In sequential case one queue can occur in front of the decoupling location and the other one in front of the runway, or there might be a case where there is an obstacle before reaching the decoupling location. Alternatively, there might be sequential decoupling locations which had to be designed in that way due to other restrictions.

The main intention of this study is to evaluate the benefits and drawbacks of having single and several decoupling locations in parallel or sequential infrastructures, simulating the aircraft queues at decoupling location/s for different settings arrival and service rates and various distributions.

The main benefits of having extra decoupling locations are reducing the sizes of aircraft queues at the airport area, decreasing the waiting times before takeoff. The decrease in queue sizes also creates free space in the airport area. The drawbacks are not fully utilizing the allocated locations, increasing the ratio of idle times when arrival frequencies are low. Low utilization of a system brings indirect costs of not using the airport area or resources for alternative operations.

As a result of this study, we aim to gain a high-level insight on how many decoupling locations can decrease the queue sizes and waiting times without increasing idle times too much. That is, a compromised solution over the conflicting objectives such as utilization and queue size is aimed to be inferred.

As simulation results, we present the expected waiting times in the queue/s and in the system -queues and decoupling/delay locations -, expected number of aircraft in the queue and in the system, utilization of system based on ratios of idle and busy times.

As we mentioned in previous paragraphs when queueing systems satisfy certain stochastic conditions, queue statistics can be computed using mathematical formulations derived from “Queueing Theory” without the need to apply a simulation method. Satisfying these stochastic conditions means that it is known beforehand that queue size will not go to infinity in the long run. In these types of instances, stochastic processes of queueing models approach “steady state” in the very long run and for this state we can compute the expected waiting times and expected number of aircraft in the queue. For the scenarios which are suitable for this case, we compute the outputs without using simulation. For the same instances, we also apply simulation. Results show that the outputs of long-term simulation (i.e., simulation of 1000 aircraft arrivals) are not highly different than the outputs of “steady state” results (for the very long term). This shows that simulation outputs can be relied upon, and we use simulation for all other scenarios when “steady state” conditions do not exist.

In addition to a set of preliminary tests, we simulate the arrivals of Large and Heavy aircraft based on ATC separation guidelines and safety buffers, and different frequencies of aircraft arrivals and service rates based on Markovian and General distributions.

We repeat simulations for each scenario with 10, 100, 1000 aircraft arrivals.

We simulate 3 ATC based scenarios with 1 to 5 parallel decoupling locations and with 10, 100, 1000 aircraft arrivals considering separation guidelines and safety buffers. In ATC based scenarios arrivals are generated in three different ways: (1) using Poisson distribution with an arrival rate respecting a mean interarrival time obtained by considering ATC separation guidelines and safety buffers for Large and Heavy aircraft, (2) using an ATC based roulette wheel approach, (3) using Normal distribution with ATC based mean interarrival time and standard deviation, Unlike (1) and (3), (2) simulates exactly the heterogeneous, since (1) and (3) use the average obtained from probability matrices and trailing restrictions.

To test more general cases with higher and less frequent aircraft arrivals, we gradually increase arrival rates and at each increase we break the steady state condition for one more decoupling location – but not for additional ones - in which case the queue size is expected to go to infinity with corresponding number of decoupling locations and report the findings. However, queue sizes in these cases can still be controlled by adding one extra decoupling location.

To test highly slow decoupling durations, we generate longer decoupling durations - using a very low decoupling service rate in related probability distribution-. These scenarios result in queue sizes going to infinity, and comments are provided when waiting times can be reduced but they are never eliminated. The best solution would be to arrange arrival frequency accordingly unless service time cannot be decreased.

We also test sequential systems. Sequential systems include a set of delay locations on the path to runway. We simulate the case with two sequential queues. In this case, a sequential set of queues could mean: (1) the case when the first queue occurs in front of the decoupling location, and the second queue occurs in front of the runway, (2) the case when there is a collision point before reaching to decoupling location and the first queue occurs at this collision point, and the second queue is in front of the decoupling location, (3) the case when there is a sequential design of decoupling locations which is not very likely. We evaluate the results.

3.2.2 Models

In models with single queue and single decoupling location, aircraft arrive at a single queue, wait for the decoupling location to be free and enter the location which has a unit capacity when it becomes free and leave the system after being decoupled to head to the runway. Representation of single queue single decoupling location is given in Figure 16.

In models with single queue and multiple parallel decoupling locations, aircraft arrive at a single queue, wait for one of the decoupling locations to be free and enter the location that becomes free earlier than others and has a unit capacity and leave the system after being decoupled to head to the runway. In these systems decoupling operations of several aircraft can be handled in parallel at different locations. Representation of parallel decoupling locations is given in Figure 17.

In sequential systems, aircraft arrives at the first queue in front of a decoupling location, wait for the location to be free and leave the system after a while and enter a second queue in front of the next delay location which might be a second decoupling location or another obstacle that is blocking the way to runway or the runway itself occupied by other aircraft or tasks. It can also be interpreted as the first delay location being an obstacle on the path to a decoupling location and second delay location is the decoupling location itself. A representation of a sequential system is given in Figure 18. In Figure 18, first delay location is a decoupling point. The second delay point is the runway or an occupied area before reaching the runway,

In ATC based models, transition probability matrices of arrivals of heavy and large aircraft and ATC restrictions and safety buffers for leading-trailing aircraft pairs such as heavy after heavy, large after heavy, heavy after large, ... etc. are taken into consideration in single and multiple parallel server systems.

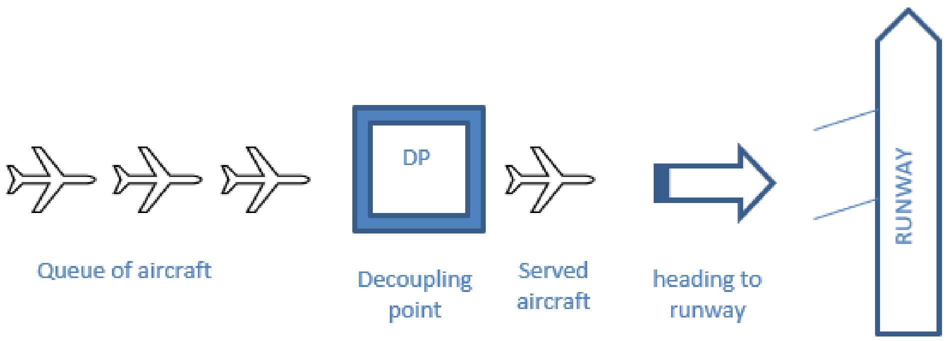

Figure 16: Representation of single queue single decoupling location

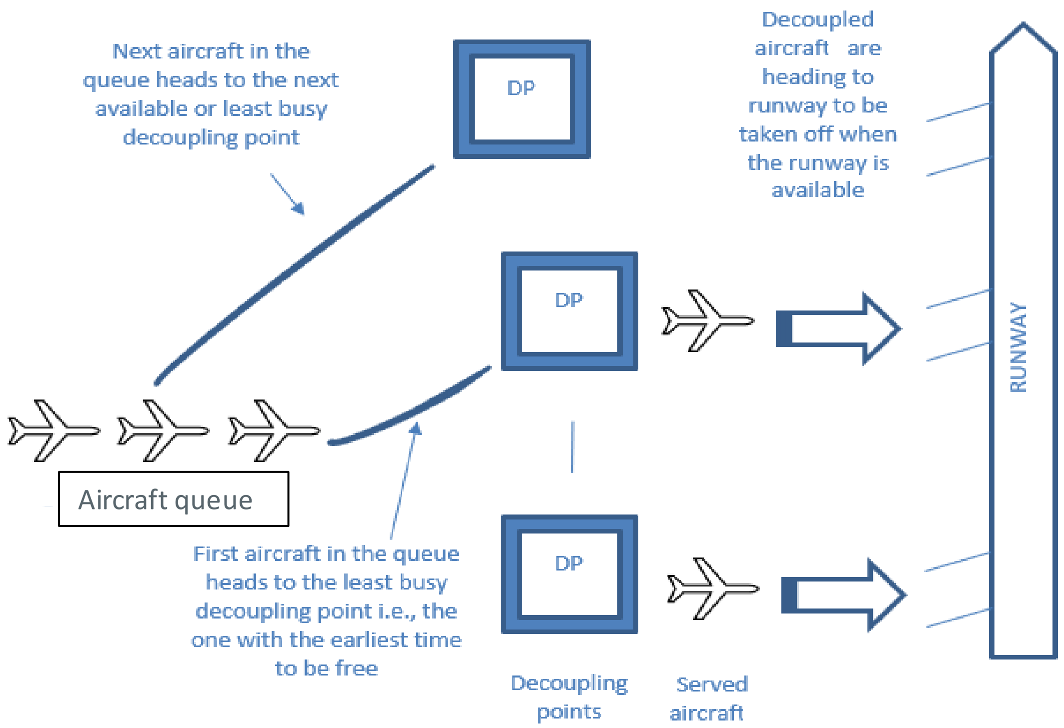

Figure 17: Representation of single queue multiple parallel decoupling locations

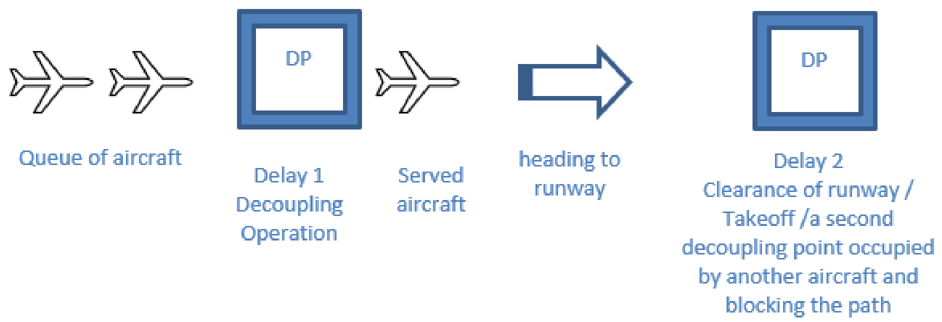

Figure 18 : Representation of an example of sequential delay locations

3.2.3 Methodology

We use discrete event simulation method for simulating parallel and sequential systems. We use various probability distributions or roulette wheel selection to generate arrival times and interarrival distributions of aircraft at decoupling locations. We generate decoupling durations using exponential distribution. After a number of simulations, we generate simulation tables which show the time aircraft enter the system, start being decoupled, leave the system, the remaining times of servers to become free, and total times spent in the system. We also generate simulation timelines which show when a Large, Heavy or a unique type aircraft arrives at and leave the system exactly and the numbers of aircraft existing at the system until a new event occurs. In result tables, we show expected waiting times of aircrafts in the queue (Wq), expected waiting times of aircraft in the system (Ws), expected number of aircraft in the queue (Lq), expected number of aircraft in the system (Ls), and utilization (U). As an alternative, we use steady state probabilities if applicable.

3.2.4 Results for simulation of aircraft arrivals based on ATC separation guidelines and safety buffers

We present here only the results of ATC based scenarios as an example among many other parallel system scenarios that we simulated. Other simulated parallel system scenarios are scenarios with high and low frequency of aircraft arrivals and scenarios with highly slow service rates as described in Introduction section.

We generate aircraft arrivals in three different ways in ATC based scenarios:

1) Poisson arrivals having an arrival rate derived by using a mean interarrival time for heavy and large aircraft arrivals based on ATC separation guidelines and a homogeneous type of fleet is assumed to be arriving although the mean has the information of heterogeneous arrivals,

(2) A roulette wheel approach for generating arrivals that exactly simulates the arrivals of different aircraft types such as heavy and large and creates interarrival times based on speed restrictions for leading and trailing aircraft.

(3) Normally distributed arrivals with the mean interarrival time obtained by the same way as in (1) and related standard deviation,

In the following three subsections we explain these scenarios and related results:

3.2.4.1 Scenarios with ATC based Poisson arrivals

This scenario is denoted as follows:

M/M/c|poisson, λ:0.47|exp, μ:1|(ATC)?: YES|(λ<n_dp*μ)?: Y, λ<μ, λ<2μ, λ<3μ, λ<4μ, λ<5μ|L,H,homogenized

In this scenario, M/M/1 to M/M/5, that is 1 to 5 decoupling locations with Markovian arrivals of aircraft and Markovian service times are simulated. Aircraft arrivals are generated using Poisson distribution with rate λ:0.47, and decoupling service times are generated using exponential distribution with rate μ:1, for N=10, N=100, N=1000 arrivals. Poisson rate reflects the average interarrival time, 1/0.47=2.13 minutes, that is to be respected due to ATC separation guidelines and safety buffers. "L,H,homogenized" denotes that the interarrival times of aircraft are generated considering this average interarrival time obtained using arrival probabilities of Large and Heavy aircraft and speed restrictions for each leading and trailing aircraft -instead of exactly addressing the arrivals of heterogeneous aircraft types which will be analysed in the roulette wheel case. -

Figures 19, 20, 21 show the simulation outputs for 1 to 5 decoupling locations for 10, 100, 1000 aircraft arrivals. The presented outputs are: (1) expected number of aircraft in the queue -Lq(SIM)-, (2) mean waiting times of aircraft in the queue -Wq(SIM)- (in minutes), (3) the highest waiting time in the queue (in minutes), (4) probability of having 0 aircraft in the system (queue and servers) – RATIO OF IDLE TIMES, and (5) utilization of the system, obtained by simulation. (4) and (5) take values between 0 and

1. As waiting times, (2) and (3), and expected queue size (1) decrease, ratio of expected idle states (4) increases. In contrast, ratio of occupied states, utilization (5) decreases.

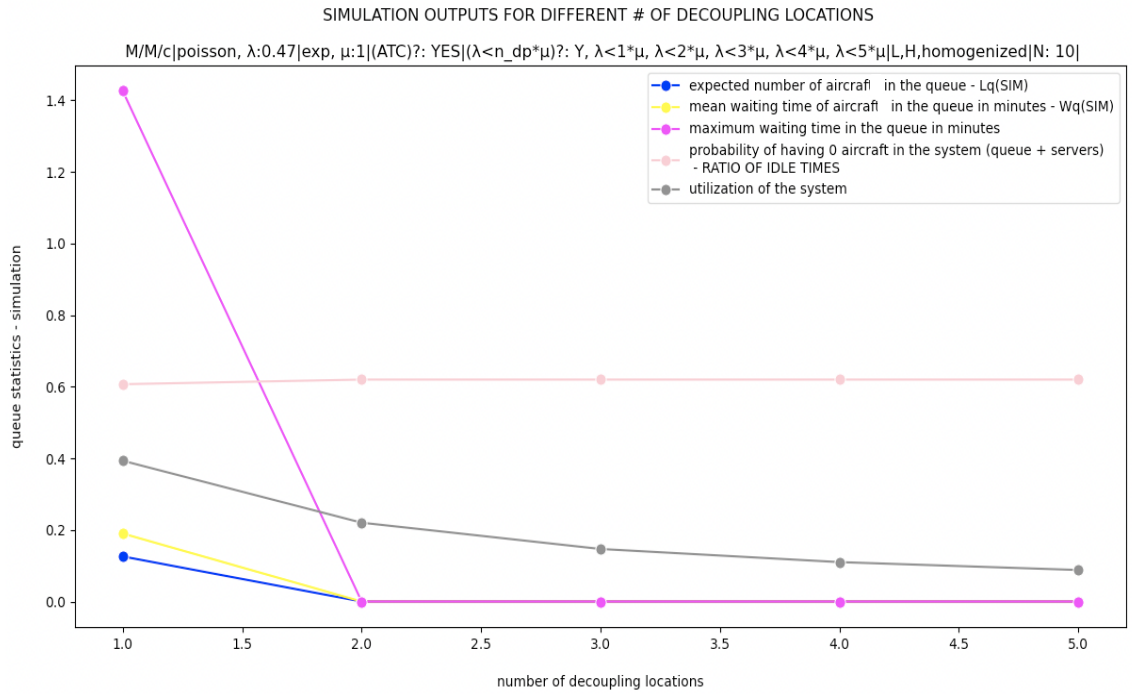

Figure 19 : Simulation outputs for M/M/c|poisson, λ:0.47|exp, μ:1|(ATC)?: YES|(λ<n_dp*μ)?: Y, λ<μ, λ<2μ, λ<3μ, λ<4μ, λ<5μ|L,H,homogenized|N=10|

In Figure 19, where the outputs of simulation of N=10 arrivals are shown, the highest waiting time observed with one decoupling location is 1.4 minute, whereas it reduces to 0 after 2 decoupling locations. Similarly, the expected number of aircraft in the queue reduces to 0 after 2 decoupling locations. Probability of having no aircraft in the system, i.e., neither waiting in the queue nor being served at decoupling locations, is quite high and increases by increasing number of decoupling locations, and in utilization of the system decreases for increasing number of decoupling locations.

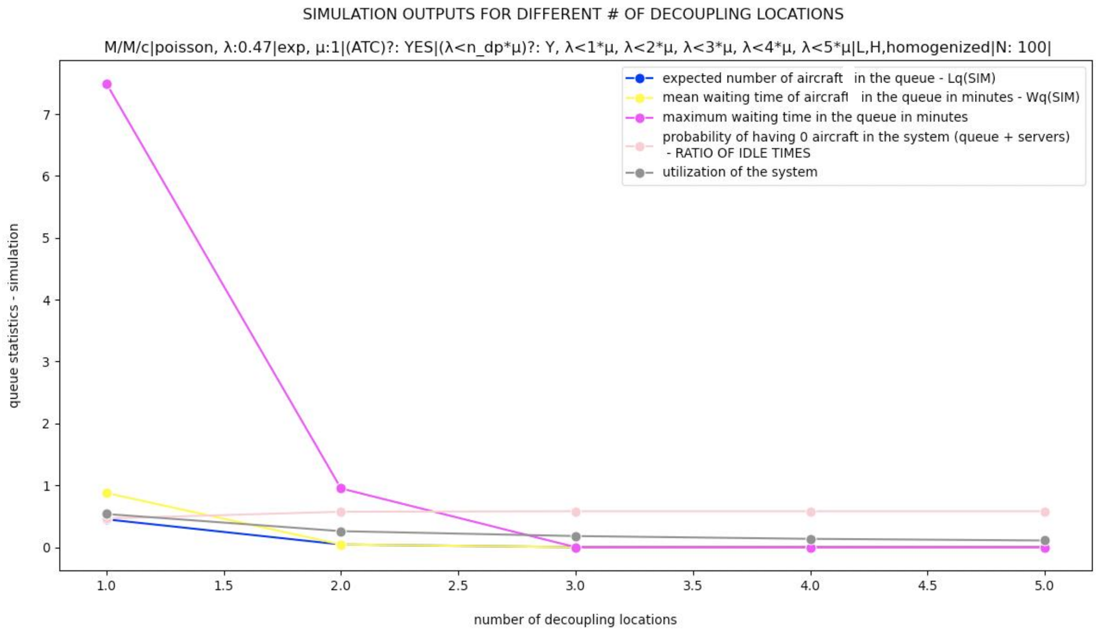

Figure 20 **: Simulation outputs for M/M/c|poisson, λ:0.47|exp, μ:1|(ATC)?: YES|(λ<n_dp*μ)?: Y, λ<μ, λ<2μ, λ<3μ, λ<4μ, λ<5μ|L,H,homogenized|N=100|**

Figure 20 demonstrates the simulation results for 100 aircraft arrivals. Results are similar except that for this longer-term simulation the highest waiting time in the queue is 7 minutes, although the mean is not so high. The highest waiting time value is being reduced to 1 minute by adding the second decoupling location and all waiting times are reduced to 0 by adding the third decoupling location.

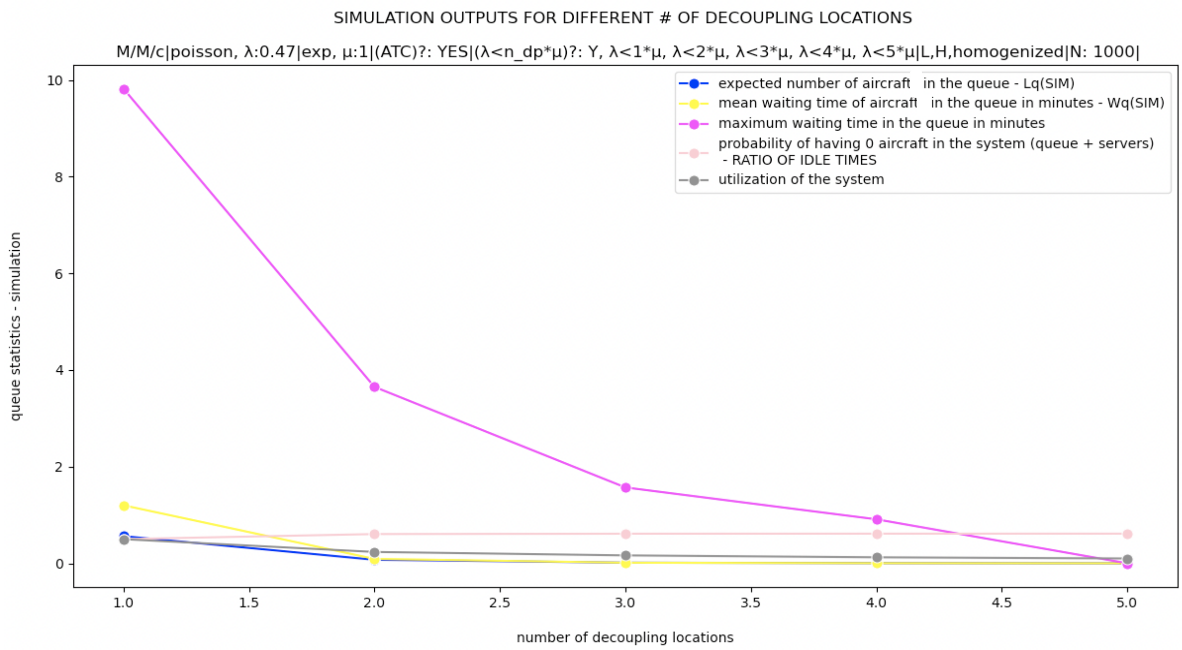

Figure 21 **:** Simulation outputs for M/M/c|poisson, λ:0.47|exp, μ:1|(ATC)?: YES|(λ<n_dp*μ)?: Y, λ<μ, λ<2μ, λ<3μ, λ<4μ, λ<5μ|L,H,homogenized|N=1000|

Due to the simulation outputs with 1000 arrivals in Figure 21, the highest waiting time for one decoupling location is 10 minutes, which decreases to 4 minutes by adding the second decoupling location, and to 2 minutes by adding the third one. Mean waiting time is less than 2 minutes for one decoupling location and approaches to 0 for additional ones.

Distributions of interarrival and service times for 10, 100, 1000 arrivals are given in Figures 22, 23, 24 as examples:

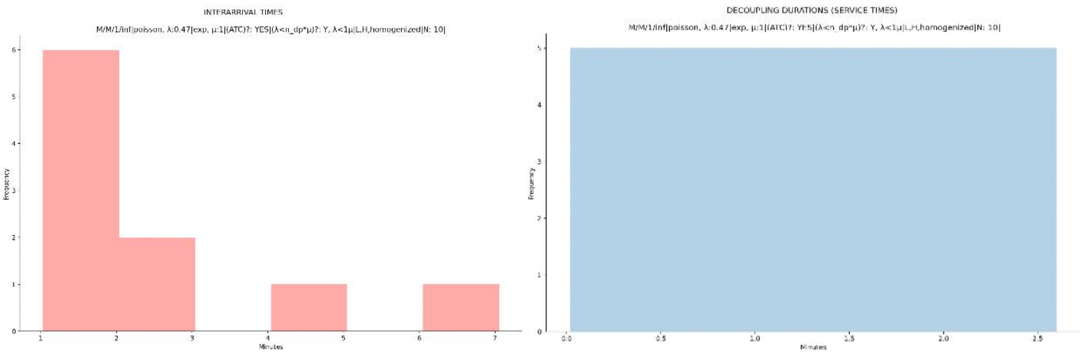

Figure 22 : Interarrival times of aircraft (left) and service times (right) for M/M/c|poisson, λ:0.47|exp, μ:1|(ATC)?: YES|(λ<n_dp*μ)?: Y, λ<μ, λ<2μ, λ<3μ, λ<4μ, λ<5μ|L,H,homogenized|N=10|

Histograms of interarrival and service times generated for 10 arrivals are plotted in Figure 22. Exact values of these interarrival and service times for 10 aircraft can also be observed in “interarrival times” and “services times” columns of the simulation table in Table 7.

Table 7: Simulation table for M/M/1|poisson, λ:0.47|exp, μ:1|(ATC)?: YES|(λ<n_dp*μ)?: Y, λ<μ| L,H,homogenized|N=10|

SIM TABLE –
M/M/1/inf|poisson, λ:0.47|exp, μ:1|(ATC)?: YES|(λ<n_dp∗μ)?: Y, λ<1μ|L,H,homogenized|N: 10|

	interarrival_times	arrival_times	servers_minr	waiting_times	start_times	service_times	finish_times	total_times
0	1.693350	1.6934	0.0000	0.0000	1.6934	1.568896	3.2623	1.5689
1	2.672193	4.3656	3.2623	0.0000	4.3656	0.752674	5.1183	0.7527
2	1.964305	6.3299	5.1183	0.0000	6.3299	0.839433	7.1693	0.8394
3	1.674896	8.0048	7.1693	0.0000	8.0048	2.598254	10.6031	2.5983
4	1.172444	9.1772	10.6031	1.4259	10.6031	0.073685	10.6768	1.4996
5	2.208850	11.3860	10.6768	0.0000	11.3860	0.091161	11.4772	0.0912
6	1.224509	12.6105	11.4772	0.0000	12.6105	0.020426	12.6309	0.0204
7	4.730903	17.3414	12.6309	0.0000	17.3414	1.787488	19.1289	1.7875
8	7.053005	24.3944	19.1289	0.0000	24.3944	1.505784	25.9002	1.5058
9	1.028941	25.4233	25.9002	0.4769	25.9002	2.040314	27.9405	2.5172

Histograms of interarrival and service times generated for 100 arrivals are plotted in Figure 23. Exact values of interarrival and service times are seen in related columns of Table 8.

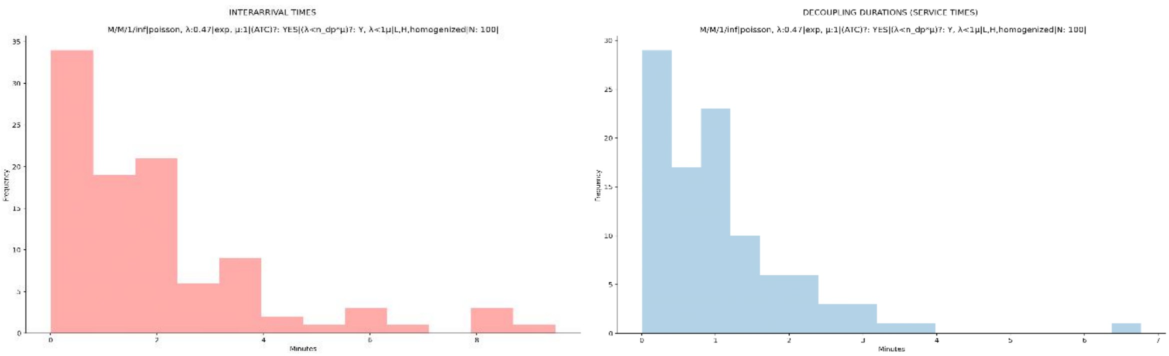

Figure 23: Interarrival times of aircraft (left) and service times (right) for M/M/c|poisson, λ:0.47|exp, µ:1|(ATC)?: YES|(λ<n_dp*µ)?: Y, λ<µ, λ<2µ, λ<3µ, λ<4µ, λ<5µ|L,H,homogenized|N=100|

Table 8: Simulation table for M/M/1|poisson, λ:0.47|exp, µ:1|(ATC)?: YES|(λ<n_dp*µ)?: Y, λ<µ| L,H,homogenized|N=100|

SIM TABLE -
M/M/1/inf|poisson, λ:0.47|exp, µ:1|(ATC)?: YES|(λ<n_dp*µ)?: Y, λ<1µ|L,H,homogenized|N: 100|

	interarrival_times	arrival_times	servers_minr	waiting_times	start_times	service_times	finish_times	total_times
0	1.693350	1.6934	0.0000	0.0000	1.6934	1.132634	2.8260	1.1326
1	2.672193	4.3656	2.8260	0.0000	4.3656	0.314722	4.6803	0.3147
2	1.964305	6.3299	4.6803	0.0000	6.3299	1.328758	7.6587	1.3288
3	1.674896	8.0048	7.6587	0.0000	8.0048	3.275143	11.2799	3.2751
4	1.172444	9.1772	11.2799	2.1027	11.2799	0.286021	11.5659	2.3887
..	...	...	...	...	...	...	...	...
95	0.430533	189.7682	192.8452	3.0770	192.8452	0.674245	193.5194	3.7512
96	1.878998	191.6472	193.5194	1.8722	193.5194	0.258013	193.7774	2.1302
97	0.043218	191.6904	193.7774	2.0870	193.7774	0.293508	194.0709	2.3805
98	3.756896	195.4473	194.0709	0.0000	195.4473	0.059781	195.5071	0.0598
99	0.010014	195.4573	195.5071	0.0498	195.5071	0.569898	196.0770	0.6197

Histograms of interarrival and service times generated for 1000 arrivals are plotted in Figure 24. Exact values of interarrival and service times are seen in related columns of Table 9.

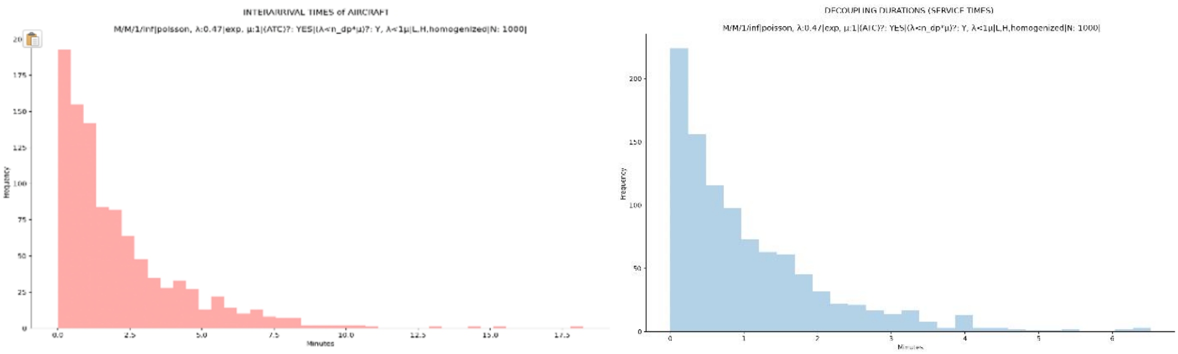

Figure 24: Interarrival times of aircraft (left) and service times (right) for M/M/c|poisson, λ:0.47|exp, µ:1|(ATC)?: YES|(λ<n_dp*µ)?: Y, λ<µ, λ<2µ, λ<3µ, λ<4µ, λ<5µ|L,H,homogenized| N=1000|

Table 9: Simulation table for M/M/1|poisson, λ:0.47|exp, µ:1|(ATC)?: YES|(λ<n_dp*µ)?: Y, λ<µ| L,H,homogenized|N=1000|

SIM TABLE -
M/M/1/inf|poisson, λ:0.47|exp, µ:1|(ATC)?: YES|(λ<n_dp*µ)?: Y, λ<1µ|L,H,homogenized|N: 1000|

	interarrival_times	arrival_times	servers_minr	waiting_times	start_times	service_times	finish_times	total_times
0	1.693350	1.6934	0.0000	0.0000	1.6934	0.898648	2.5920	0.8986
1	2.672193	4.3656	2.5920	0.0000	4.3656	0.010115	4.3757	0.0101
2	1.964305	6.3299	4.3757	0.0000	6.3299	0.645932	6.9758	0.6459
3	1.674896	8.0048	6.9758	0.0000	8.0048	1.233643	9.2384	1.2336
4	1.172444	9.1772	9.2384	0.0612	9.2384	0.044972	9.2834	0.1062
..	...	...	...	...	...	...	...	...
995	0.218685	2124.7643	2125.0808	0.3165	2125.0808	1.566769	2126.6476	1.8833
996	1.539247	2126.3035	2126.6476	0.3441	2126.6476	1.277254	2127.9249	1.6214
997	5.930401	2132.2339	2127.9249	0.0000	2132.2339	0.654134	2132.8880	0.6541
998	0.552359	2132.7863	2132.8880	0.1017	2132.8880	1.032443	2133.9204	1.1341
999	2.405404	2135.1917	2133.9204	0.0000	2135.1917	0.696700	2135.8884	0.6967

Simulation results for 10, 100, 10000 arrivals are given in Tables 10, 11, 12. Ls(SIM) is the expected number of aircraft in the system, Lq(SIM) is the expected number of aircraft in the queue -obtained by simulation-, Ws(SIM) is the expected waiting time in the system, Wq(SIM)is the expected waiting time in the queue, and U(SIM) is the utilization of the system. Waiting times are in terms of minutes and utilization is a ratio between 0 and 1.

Table 10: Simulation results for M/M/c|poisson, λ:0.47|exp, μ:1|(ATC)?: YES|(λ<n_dp*μ)?: Y, λ<μ, λ<2μ, λ<3μ, λ<4μ, λ<5μ|L,H,homogenized|N=10|

	Queueing Model	Arrivals	Service	(ATC)?	(λ<n_dp*μ)?	n_dp	fleet	N	Ls(SIM)	Lq(SIM)	Ws(SIM)	Wq(SIM)	U(SIM)
0	M/M/1/inf	poisson, λ:0.47	exp, μ:1	YES	Y, λ<1μ	1	L,H,homogenized	10	0.52	0.126	1.318	0.19	0.393
1	M/M/2/inf	poisson, λ:0.47	exp, μ:1	YES	Y, λ<2μ	2	L,H,homogenized	10	0.441	0	1.128	0	0.22
2	M/M/3/inf	poisson, λ:0.47	exp, μ:1	YES	Y, λ<3μ	3	L,H,homogenized	10	0.441	0	1.128	0	0.147
3	M/M/4/inf	poisson, λ:0.47	exp, μ:1	YES	Y, λ<4μ	4	L,H,homogenized	10	0.441	0	1.128	0	0.11
4	M/M/5/inf	poisson, λ:0.47	exp, μ:1	YES	Y, λ<5μ	5	L,H,homogenized	10	0.441	0	1.128	0	0.088

Table 11: Simulation results for M/M/c|poisson, λ:0.47|exp, μ:1|(ATC)?: YES|(λ<n_dp*μ)?: Y, λ<μ, λ<2μ, λ<3μ, λ<4μ, λ<5μ|L,H,homogenized|N=100|

	Queueing Model	Arrivals	Service	(ATC)?	(λ<n_dp*μ)?	n_dp	fleet	N	Ls(SIM)	Lq(SIM)	Ws(SIM)	Wq(SIM)	U(SIM)
0	M/M/1/inf	poisson, λ:0.47	exp, μ:1	YES	Y, λ<1μ	1	L,H,homogenized	100	0.986	0.45	1.928	0.877	0.536
1	M/M/2/inf	poisson, λ:0.47	exp, μ:1	YES	Y, λ<2μ	2	L,H,homogenized	100	0.561	0.043	1.094	0.043	0.259
2	M/M/3/inf	poisson, λ:0.47	exp, μ:1	YES	Y, λ<3μ	3	L,H,homogenized	100	0.539	0	1.051	0	0.18
3	M/M/4/inf	poisson, λ:0.47	exp, μ:1	YES	Y, λ<4μ	4	L,H,homogenized	100	0.539	0	1.051	0	0.135
4	M/M/5/inf	poisson, λ:0.47	exp, μ:1	YES	Y, λ<5μ	5	L,H,homogenized	100	0.539	0	1.051	0	0.108

Table 12: Simulation results for M/M/c|poisson, λ:0.47|exp, μ:1|(ATC)?: YES|(λ<n_dp*μ)?: Y, λ<μ, λ<2μ, λ<3μ, λ<4μ, λ<5μ|L,H,homogenized|N=1000|

	Queueing Model	Arrivals	Service	(ATC)?	(λ<n_dp*μ)?	n_dp	fleet	N	Ls(SIM)	Lq(SIM)	Ws(SIM)	Wq(SIM)	U(SIM)
0	M/M/1/inf	poisson, λ:0.47	exp, μ:1	YES	Y, λ<1μ	1	L,H,homogenized	1000	1.061	0.562	2.266	1.2	0.499
1	M/M/2/inf	poisson, λ:0.47	exp, μ:1	YES	Y, λ<2μ	2	L,H,homogenized	1000	0.542	0.073	1.158	0.091	0.235
2	M/M/3/inf	poisson, λ:0.47	exp, μ:1	YES	Y, λ<3μ	3	L,H,homogenized	1000	0.505	0.013	1.078	0.012	0.164
3	M/M/4/inf	poisson, λ:0.47	exp, μ:1	YES	Y, λ<4μ	4	L,H,homogenized	1000	0.5	0.003	1.068	0.002	0.124
4	M/M/5/inf	poisson, λ:0.47	exp, μ:1	YES	Y, λ<5μ	5	L,H,homogenized	1000	0.499	0	1.066	0	0.1

In tables 7, 8, 9, it can also be observed that for simulation with N=10 arrivals, expected waiting times of aircraft in the queue and expected number of aircraft in the queue can be reduced to 0 by using two decoupling locations. By simulation with N=100 aircraft, this can be achieved by 3 decoupling locations. For N=1000 arrivals, expected waiting time and expected number of aircraft in the queue are 0 only when there are 5 decoupling locations, however they are close to 0 with 2,3,4 decoupling locations too.

For these scenarios, it is also possible to find out the queue behaviors in the very long term, that is for an infinite number of aircraft arrivals, since these instances meet certain stochastic conditions. These results are given in Tables 10 and 11.

Table 13: Steady state results for M/M/1|poisson, λ:0.47|exp, μ:1|(ATC)?: YES|(λ<n_dp*μ)?: Y, λ<μ|L,H,homogenized

	Queueing Model	Arrivals	Service	(ATC)?	(λ<n_dp*μ)?	Ls(STEADY)	Lq(STEADY)	Ws(STEADY)	Wq(STEADY)	U(STEADY)
0	M/M/1	poisson, λ:0.47	exp, μ:1	YES	Y, λ<1μ	0.887	0.417	1.887	0.887	0.47

Table 14: Steady state results for M/M/c|poisson, λ:0.47|exp, μ:1|(ATC)?: YES|(λ<n_dp*μ)?: Y, λ<μ|L,H,homogenized

	Queueing Model	Arrivals	Service	(ATC)?	(λ<n_dp*μ)?	n_dp	fleet	N	Lq(STEADY)	Wq(STEADY)	U(STEADY)
0	M/M/2/inf	poisson, λ:0.47	exp, μ:1	YES	Y, λ<2μ	2	L,H,homogenized	NA	0.114	0.244	0.235
1	M/M/3/inf	poisson, λ:0.47	exp, μ:1	YES	Y, λ<3μ	3	L,H,homogenized	NA	0.018	0.038	0.157
2	M/M/4/inf	poisson, λ:0.47	exp, μ:1	YES	Y, λ<4μ	4	L,H,homogenized	NA	0.002	0.005	0.117
3	M/M/5/inf	poisson, λ:0.47	exp, μ:1	YES	Y, λ<5μ	5	L,H,homogenized	NA	0	0	0.094

The findings regarding the queue behaviors at infinity (Table 13 and 14) which are found using stochastic equations rather than simulation are similar to the findings of simulation with N=1000 arrivals. According to outputs in Table 10 and 11, using 5 decoupling locations reduces all waiting times and expected number of aircraft in the queue to 0, but also with 2, 3, 4 decoupling locations are close to 0 like the case in Table 9. Thus, allocating 2 decoupling locations is acceptable in this scenario.

3.2.4.2 Scenarios with ATC based roulette wheel arrivals

This scenario is labelled as follows: G/M/c|roulette, ATC|exp, μ:1|(ATC)?: YES|(λ<n_dp*μ)?: NA|L,H,heterogeneous

In this case arrivals of Large and Heavy aircraft are generated using roulette wheel selection considering the probabilities that arriving aircraft are Heavy or Large. For simplicity, Small aircraft are assumed to be Large, thus arrivals of Heavy aircraft are generated with a probability of 0.2 and arrivals of Large ones are generated with probability of 0.8. Interarrival times are set based on ATC separation guidelines and safety buffers regarding the maximum speed that a trailing aircraft can have and minimum interarrival time that needs to be respected. Distributions of service times are the same as in the previous scenarios. Distributions of interarrivals of aircraft derived from arrivals with respect to roulette wheel selection and ATC guidelines are given in Figures 25, 26, 27 for 10, 100, 1000 arrivals:

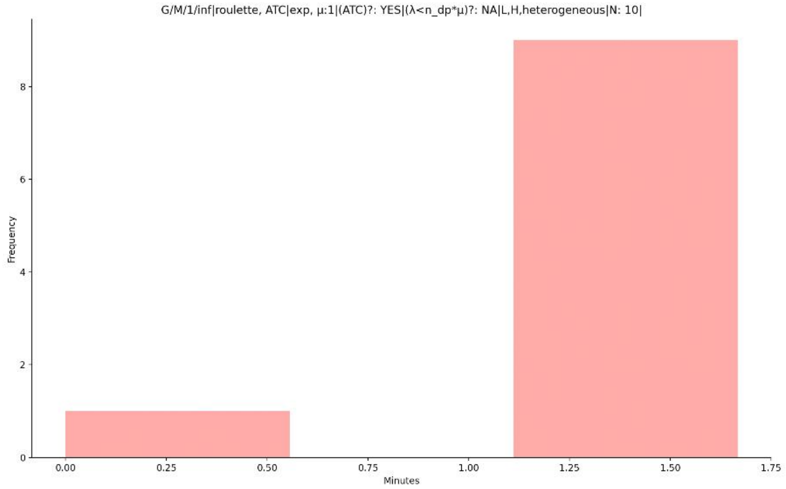

Figure 25 : Interarrival times of aircraft for G/M/c|roulette, ATC|exp, μ:1 (ATC)?: YES|(λ<n_dp*μ)?: NA|L,H,heterogeneous|N=10|

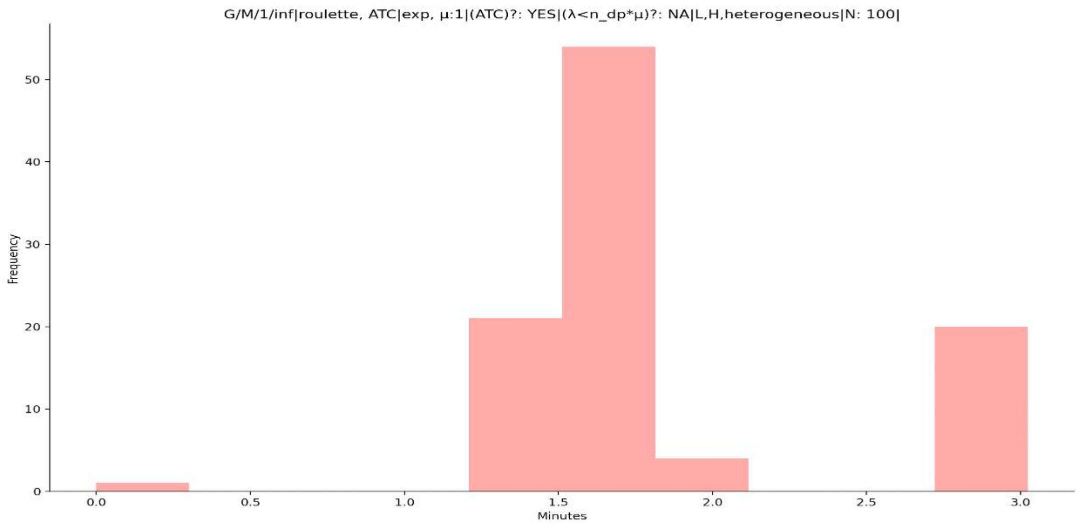

Figure 26: Interarrival times of aircraft for G/M/c|roulette, ATC|exp, μ:1 (ATC)?: YES|(λ<n_dp*μ)?: NA|L,H,heterogeneous|N=100|

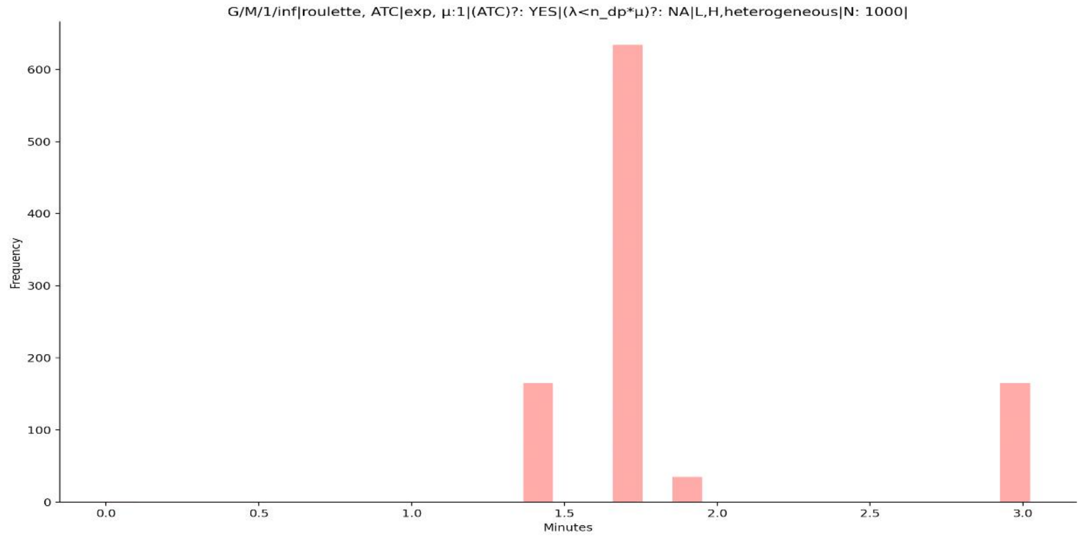

Figure 27: Interarrival times of aircraft for G/M/c|roulette, ATC|exp, μ:1 (ATC)?: YES|(λ<n_dp*μ)?: NA|L,H,heterogeneous|N=1000|

Results are given in Tables 15, 16, 17 and plotted in Figures 28, 29, 30 for 10, 100, 1000 arrivals. Accordingly, the highest waiting times are c.a. 1 minute, 5 minutes and 8 minutes for one decoupling location and 10, 100, and 1000 arrivals respectively, which seem to be better compared to ATC based Poisson arrivals scenario All waiting times are eliminated by adding the second decoupling location for 10 arrivals, and the same result is achieved by 3 decoupling locations for 100 and 1000 arrivals. With 2 decoupling locations, the highest waiting time was decreased to less than 1 and 2 minutes for 100 and 1000 arrivals, respectively.

Table 15: Simulation results for G/M/c|roulette, ATC|exp, μ:1|(ATC)?:YES|(λ<n_dp*μ)?:NA|L,H, heterogeneous|N=10|

	Queueing Model	Arrivals	Service	(ATC)?	(λ<n_dp*μ)?	n_dp	fleet	N	Ls(SIM)	Lq(SIM)	Ws(SIM)	Wq(SIM)	U(SIM)
0	G/M/1/inf	roulette, ATC	exp, μ:1	YES	NA	1	L,H,heterogeneous	10	0.605	0.062	1.233	0.105	0.543
1	G/M/2/inf	roulette, ATC	exp, μ:1	YES	NA	2	L,H,heterogeneous	10	0.547	0	1.128	0	0.274
2	G/M/3/inf	roulette, ATC	exp, μ:1	YES	NA	3	L,H,heterogeneous	10	0.547	0	1.128	0	0.182
3	G/M/4/inf	roulette, ATC	exp, μ:1	YES	NA	4	L,H,heterogeneous	10	0.547	0	1.128	0	0.137
4	G/M/5/inf	roulette, ATC	exp, μ:1	YES	NA	5	L,H,heterogeneous	10	0.547	0	1.128	0	0.109

Table 16: Simulation results for G/M/c|roulette, ATC|exp, μ:1|(ATC)?:YES|(λ<n_dp*μ)?:NA|L,H, heterogeneous|N=100|

	Queueing Model	Arrivals	Service	(ATC)?	(λ<n_dp*μ)?	n_dp	fleet	N	Ls(SIM)	Lq(SIM)	Ws(SIM)	Wq(SIM)	U(SIM)
0	G/M/1/inf	roulette, ATC	exp, μ:1	YES	NA	1	L,H,heterogeneous	100	0.714	0.157	1.346	0.295	0.557
1	G/M/2/inf	roulette, ATC	exp, μ:1	YES	NA	2	L,H,heterogeneous	100	0.559	0.004	1.055	0.004	0.278
2	G/M/3/inf	roulette, ATC	exp, μ:1	YES	NA	3	L,H,heterogeneous	100	0.557	0	1.051	0	0.186
3	G/M/4/inf	roulette, ATC	exp, μ:1	YES	NA	4	L,H,heterogeneous	100	0.557	0	1.051	0	0.139
4	G/M/5/inf	roulette, ATC	exp, μ:1	YES	NA	5	L,H,heterogeneous	100	0.557	0	1.051	0	0.111

Table 17: Simulation results for G/M/c|roulette, ATC|exp, μ:1|(ATC)?:YES|(λ<n_dp*μ)?:NA|L,H, heterogeneous|N=1000|

	Queueing Model	Arrivals	Service	(ATC)?	(λ<n_dp*μ)?	n_dp	fleet	N	Ls(SIM)	Lq(SIM)	Ws(SIM)	Wq(SIM)	U(SIM)
0	G/M/1/inf	roulette, ATC	exp, μ:1	YES	NA	1	L,H,heterogeneous	1000	0.809	0.237	1.507	0.441	0.572
1	G/M/2/inf	roulette, ATC	exp, μ:1	YES	NA	2	L,H,heterogeneous	1000	0.576	0.007	1.072	0.006	0.285
2	G/M/3/inf	roulette, ATC	exp, μ:1	YES	NA	3	L,H,heterogeneous	1000	0.572	0	1.066	0	0.191
3	G/M/4/inf	roulette, ATC	exp, μ:1	YES	NA	4	L,H,heterogeneous	1000	0.572	0	1.066	0	0.143
4	G/M/5/inf	roulette, ATC	exp, μ:1	YES	NA	5	L,H,heterogeneous	1000	0.572	0	1.066	0	0.114

As it is seen from Tables 12, 13, 14, both mean waiting time in the queue, Wq, and expected number of aircraft in the queue, Lq, are 0 with 2 decoupling locations for 10 arrivals, and almost 0 with 3 decoupling locations for 100 and 1000 arrivals.

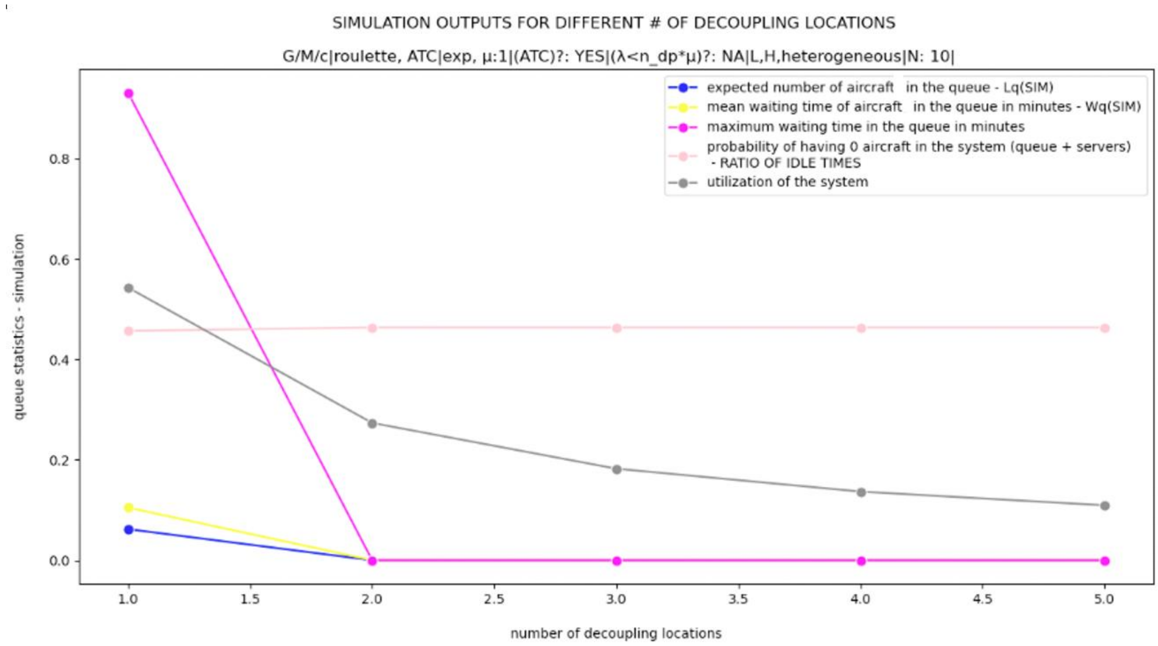

Figure 28 : Simulation outputs for G/M/c|roulette, ATC|exp, μ:1|(ATC)?:YES|(λ<n_dp*μ)?:NA|L,H, heterogeneous|N=10|

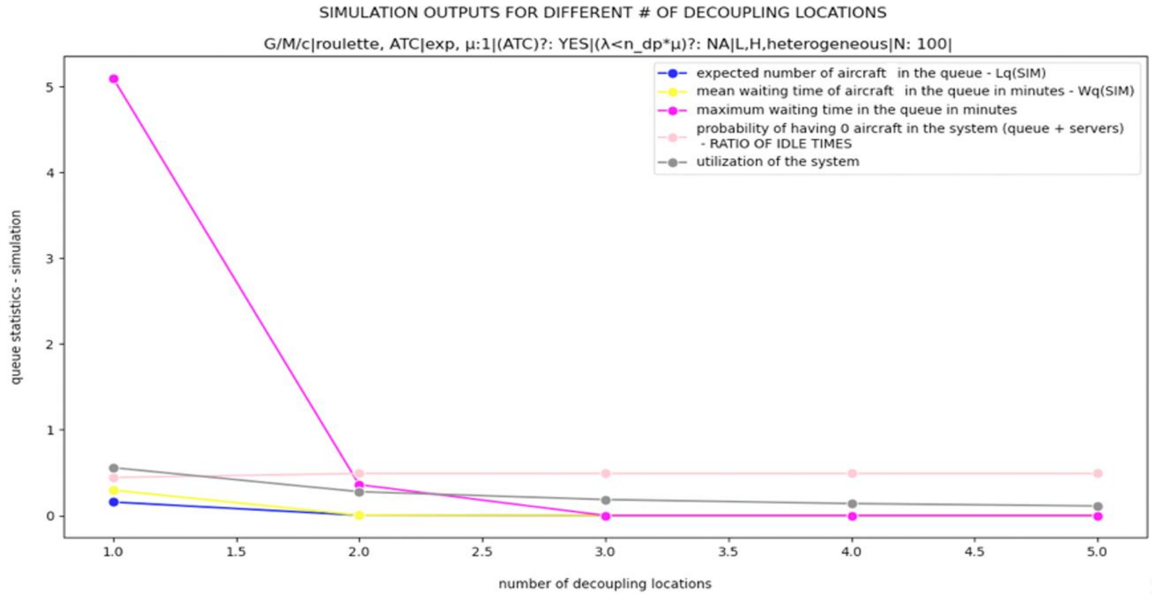

Figure 29 : Simulation outputs for G/M/c|roulette, ATC|exp, μ:1|(ATC)?:YES|(λ<n_dp*μ)?:NA|L,H, heterogeneous|N=100|

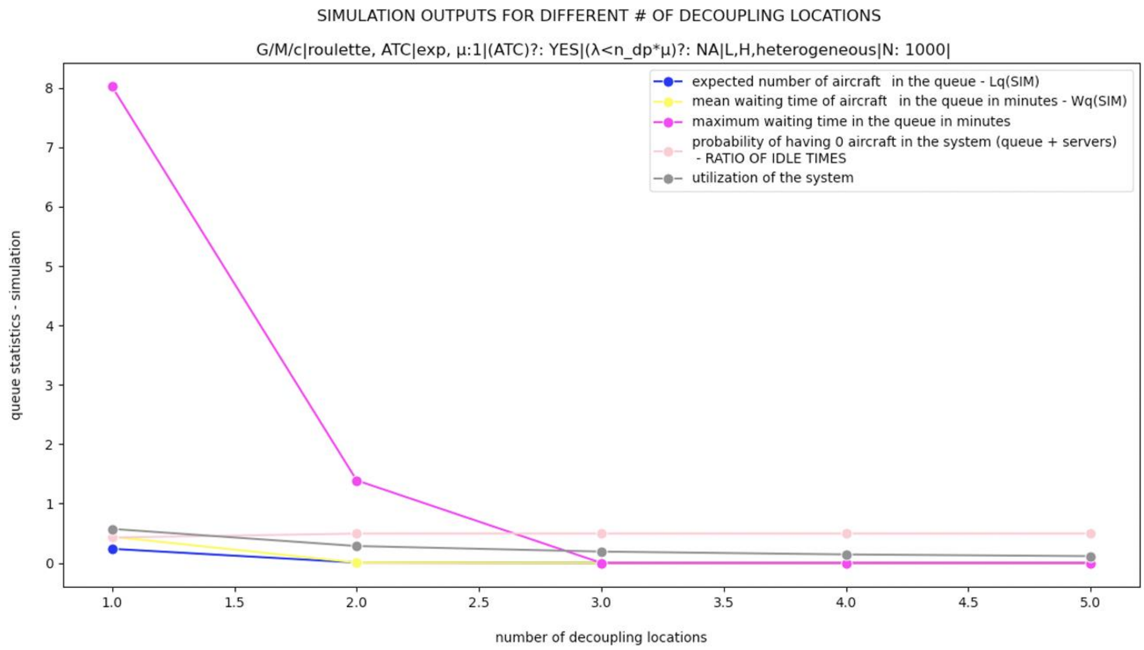

Figure 30 : Simulation outputs for G/M/c|roulette, ATC|exp, μ:1|(ATC)?:YES|(λ<n_dp*μ)?:NA|L,H, heterogeneous|N=1000|

3.2.4.3 Scenarios with ATC based normally distributed arrivals

This scenario is labelled as follows:

G/M/c|normal,(1/λ,σ):(2.13,0.68)|exp,μ:1|(ATC)?:YES|(λ<n_dp*μ)?:NA |L,H,homogenized

In this scenario, arrivals are generated using normal distribution with mean interarrival time, 2.13 minutes, and standard deviation, 0.68 minutes. The mean and std values are obtained from ATC based interarrival time restrictions, safety buffers and probabilities of arrivals of different types of aircraft as in the scenario of ATC based Poisson arrivals. Unlike ATC based Poisson arrivals, interarrivals of this scenario are more likely to occur around the mean of 2.13 minutes. Service time distributions are the same as in the previous case. Simulation tables are omitted since they have similar structures with different values. Interarrival times generated in this scenario are shown in Figures 31, 32, 33 for 10, 100, 1000 arrivals:

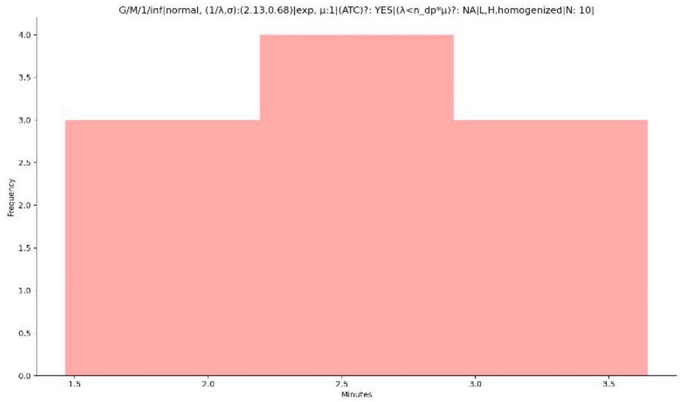

Figure 31 : Interarrival times of aircraft for G/M/c|normal,(1/λ,σ):(2.13,0.68)|exp,μ:1 |(ATC)?:YES| (λ< n_dp*μ) ? :NA |L,H,homogenized |N=10|

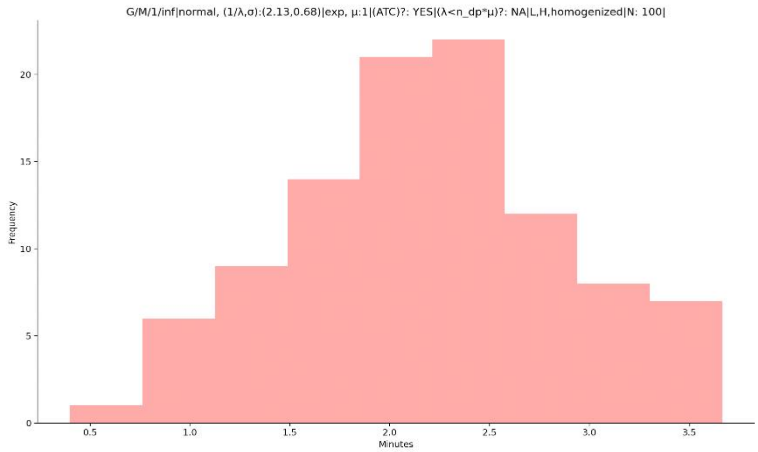

Figure 32 : Interarrival times of aircraft for G/M/c|normal,(1/λ,σ):(2.13,0.68)|exp,μ:1 |(ATC)?:YES| (λ< n_dp*μ) ? : NA |L,H,homogenized |N=100|

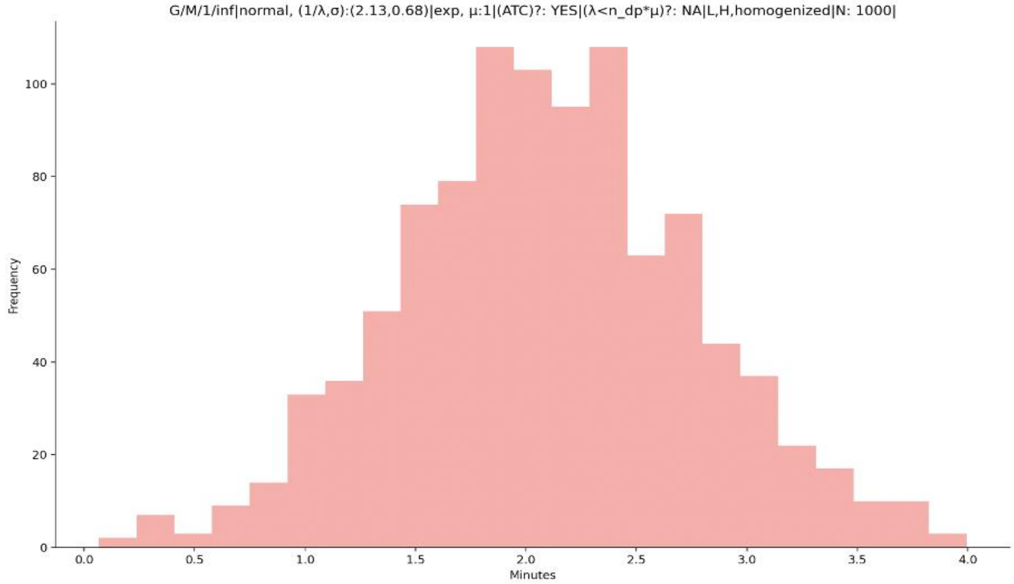

Figure 33: Interarrival times of aircraftfor G/M/c|normal,(1/λ,σ):(2.13,0.68)|exp,μ:1 |(ATC)?:YES| (λ<n_dp*μ)?:NA |L,H,homogenized |N=1000|

Results are given in Tables 18, 19, 20 and plotted in Figures 34, 35, 36 for 10, 100, 1000 arrivals. For the simulation with 10 arrivals, waiting times are already 0 with 1 decoupling location and for the simulation with 1000 arrivals having 3 decoupling locations eliminate all waiting times and decreases the expected number of aircraft to 0. For 1000 arrivals with 2 decoupling locations, expected waiting times in the queue and expected number of aircraft in the queue are still considerably low, being close to 0. In Figure 34, for 10 arrivals, mean and maximum waiting times are 0 for 1, 2, 3, 4, 5 decoupling locations. As a result of this, it is also seen that the probability of having 0 aircraft in the queue is 1 for 1, 2, 3, 4, 5 decoupling locations. In Figure 35, maximum waiting time with 1 decoupling is between 4 and 5 minutes, decreases to c.a 1 minute with 2 decoupling locations and to 0 with 3 decoupling locations. In Figure 36, maximum waiting time with 1 decoupling is around 5 minutes, decreases to a value slightly larger than 1 minute with 2 decoupling locations and to 0 with 3 decoupling locations. In both Figures 35 and 36 mean waiting times of aircraft in the queue change between 0 and 1 minutes.

Table 18: Simulation results for G/M/c |normal,(1/λ,σ): (2.13,0.68)|exp,μ:1|(ATC)?:YES|(λ < n_dp*μ) ?:NA|L,H,homogenized |N=10|

	Queueing Model	Arrivals	Service	(ATC)?	(λ<n_dp*μ)?	n_dp	fleet	N	Ls(SIM)	Lq(SIM)	Ws(SIM)	Wq(SIM)	U(SIM)
0	G/M/1/inf	normal, (1/λ,σ): (2.13,0.68)	exp, μ:1	YES	NA	1	L,H,homogenized	10	0.337	0	1.128	0	0.337
1	G/M/2/inf	normal, (1/λ,σ): (2.13,0.68)	exp, μ:1	YES	NA	2	L,H,homogenized	10	0.337	0	1.128	0	0.169
2	G/M/3/inf	normal, (1/λ,σ): (2.13,0.68)	exp, μ:1	YES	NA	3	L,H,homogenized	10	0.337	0	1.128	0	0.112
3	G/M/4/inf	normal, (1/λ,σ): (2.13,0.68)	exp, μ:1	YES	NA	4	L,H,homogenized	10	0.337	0	1.128	0	0.084
4	G/M/5/inf	normal, (1/λ,σ): (2.13,0.68)	exp, μ:1	YES	NA	5	L,H,homogenized	10	0.337	0	1.128	0	0.067

Table 19: Simulation results for G/M/c | normal,(1/λ,σ):(2.13,0.68)|exp,μ:1|(ATC)?:YES|(λ < n_dp*μ) ?:NA|L,H,homogenized |N=100|

	Queueing Model	Arrivals	Service	(ATC)?	(λ<n_dp*μ)?	n_dp	fleet	N	Ls(SIM)	Lq(SIM)	Ws(SIM)	Wq(SIM)	U(SIM)
0	G/M/1/inf	normal, (1/λ,σ): (2.13,0.68)	exp, μ:1	YES	NA	1	L,H,homogenized	100	0.576	0.133	1.263	0.287	0.444
1	G/M/2/inf	normal, (1/λ,σ): (2.13,0.68)	exp, μ:1	YES	NA	2	L,H,homogenized	100	0.448	0.009	0.985	0.01	0.22
2	G/M/3/inf	normal, (1/λ,σ): (2.13,0.68)	exp, μ:1	YES	NA	3	L,H,homogenized	100	0.444	0	0.976	0	0.148
3	G/M/4/inf	normal, (1/λ,σ): (2.13,0.68)	exp, μ:1	YES	NA	4	L,H,homogenized	100	0.444	0	0.976	0	0.111
4	G/M/5/inf	normal, (1/λ,σ): (2.13,0.68)	exp, μ:1	YES	NA	5	L,H,homogenized	100	0.444	0	0.976	0	0.089

Table 20: Simulation results for G/M/c |normal,(1/λ,σ): (2.13,0.68)|exp,μ:1|(ATC)?:YES|(λ< n_dp*μ) ?:NA|L,H,homogenized |N=1000|

	Queueing Model	Arrivals	Service	(ATC)?	(λ<n_dp*μ)?	n_dp	fleet	N	Ls(SIM)	Lq(SIM)	Ws(SIM)	Wq(SIM)	U(SIM)
0	G/M/1/inf	normal, (1/λ,σ): (2.13,0.68)	exp, μ:1	YES	NA	1	L,H,homogenized	1000	0.643	0.143	1.347	0.3	0.499
1	G/M/2/inf	normal, (1/λ,σ): (2.13,0.68)	exp, μ:1	YES	NA	2	L,H,homogenized	1000	0.501	0.004	1.051	0.004	0.249
2	G/M/3/inf	normal, (1/λ,σ): (2.13,0.68)	exp, μ:1	YES	NA	3	L,H,homogenized	1000	0.5	0	1.047	0	0.167
3	G/M/4/inf	normal, (1/λ,σ): (2.13,0.68)	exp, μ:1	YES	NA	4	L,H,homogenized	1000	0.5	0	1.047	0	0.125
4	G/M/5/inf	normal, (1/λ,σ): (2.13,0.68)	exp, μ:1	YES	NA	5	L,H,homogenized	1000	0.5	0	1.047	0	0.1

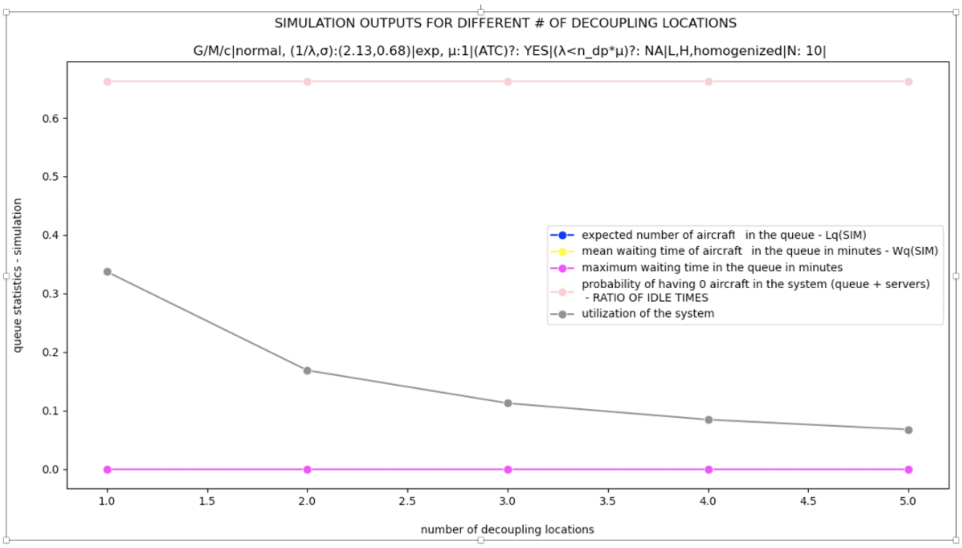

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Figure 34 : Simulation outputs for G/M/c|normal,(1/λ,σ):(2.13,0.68)|exp,μ:1|(ATC)?:YES|(λ< n_dp*μ) ?:NA|L,H,homogenized |N=10|

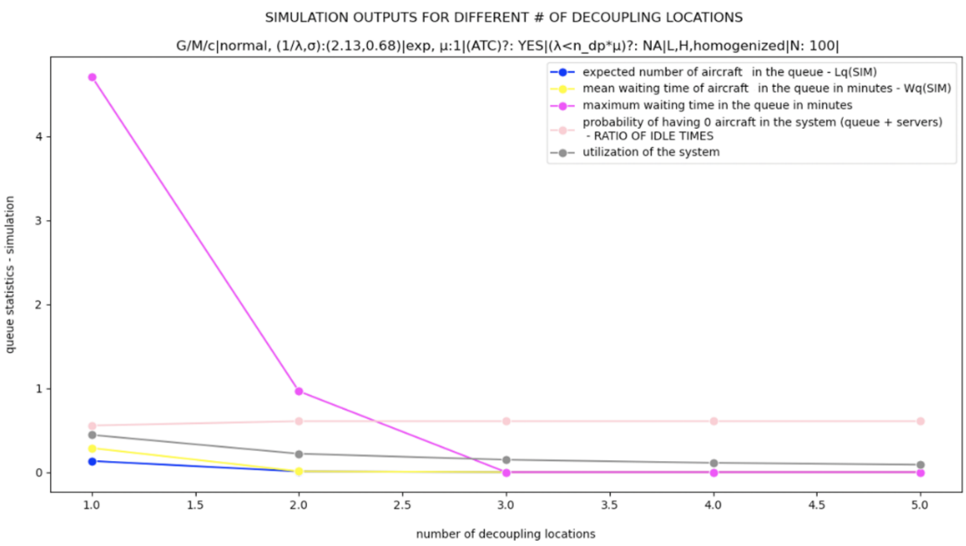


Figure 35 : Simulation outputs for G/M/c|normal,(1/λ,σ):(2.13,0.68)|exp,μ:1|(ATC)?:YES|(λ< n_dp*μ) ?:NA|L,H,homogenized |N=100|

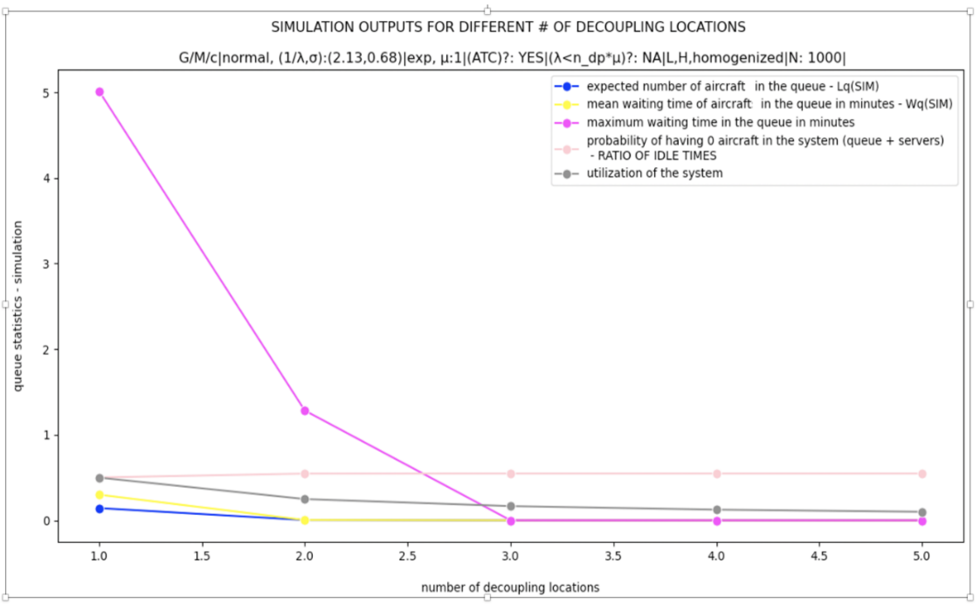
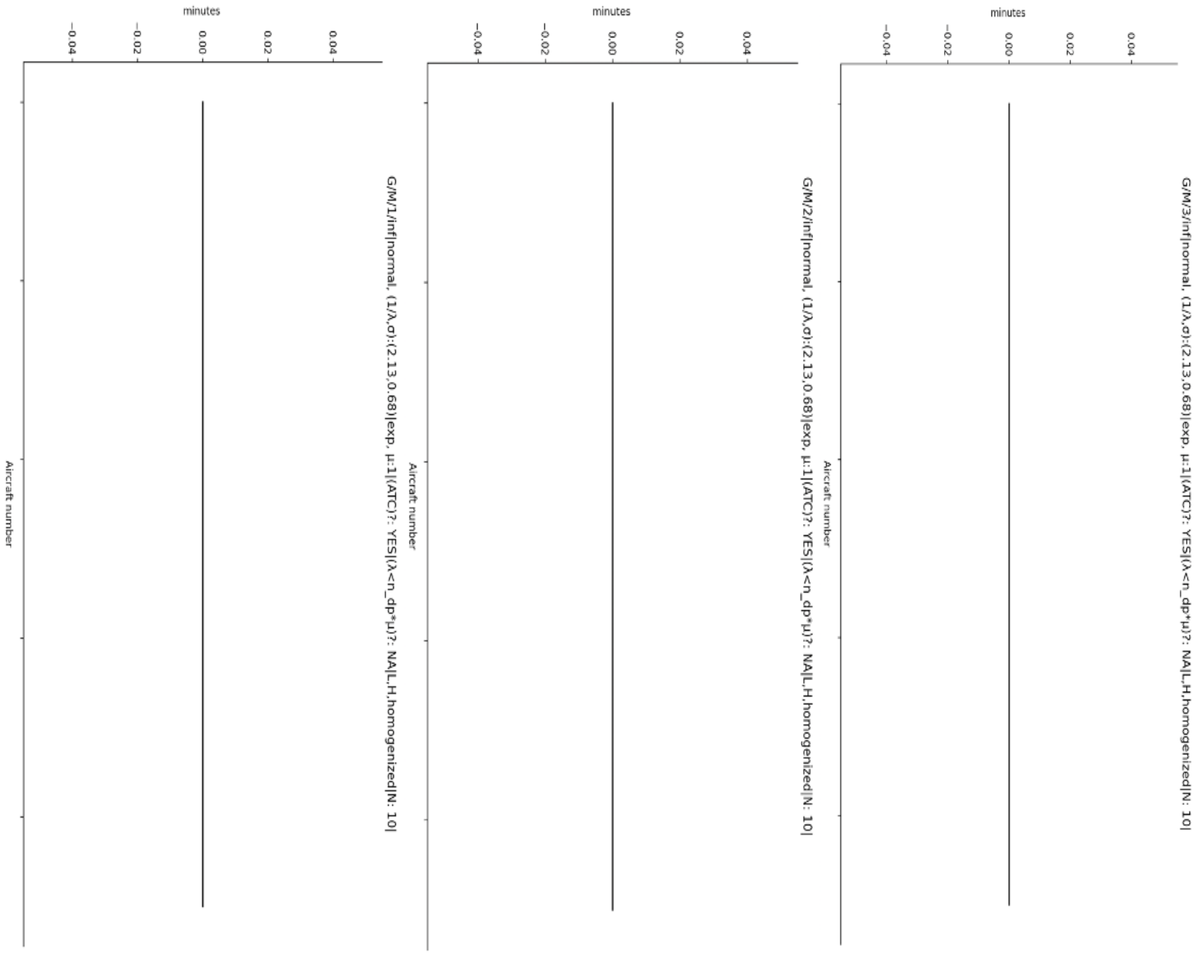


Figure 36 : Simulation outputs for G/M/c|normal,(1/λ,σ):(2.13,0.68)|exp,μ:1|(ATC)?:YES|(λ< n_dp*μ) ?:NA|L,H,homogenized |N=1000|

Another type of diagram we plot for all scenarios is waiting times of all arriving aircraft in the queue for each different number of decoupling locations separately. In Figure 37 we plot these for 10 arrivals in which case all waiting times are 0 even for 1 decoupling location. In Figure 38, waiting times for 100 aircraft are plotted and it is seen that waiting times are 0 with 3 decoupling locations and there are few nonzero waiting times with 2 decoupling locations. In Figure 39, waiting times for 1000 arrivals are plotted. In this case with 1 decoupling location, there is a high frequency of non-zero waiting times and it is seen from the figure that many of them are eliminated with 2 decoupling locations, and all of them are eliminated with 3 decoupling locations.



a. Aircraft waiting times at decoupling queue, n_dp = 1

b. Aircraft waiting times at decoupling queue, n_dp = 2

c. Aircraft waiting times at decoupling queue, n_dp = 3

Figure 37 : Aircraft waiting times at decoupling queue for N=10 arrivals and n_dp=1(a), n_dp=2(b), n_dp=3(ct) decoupling locations

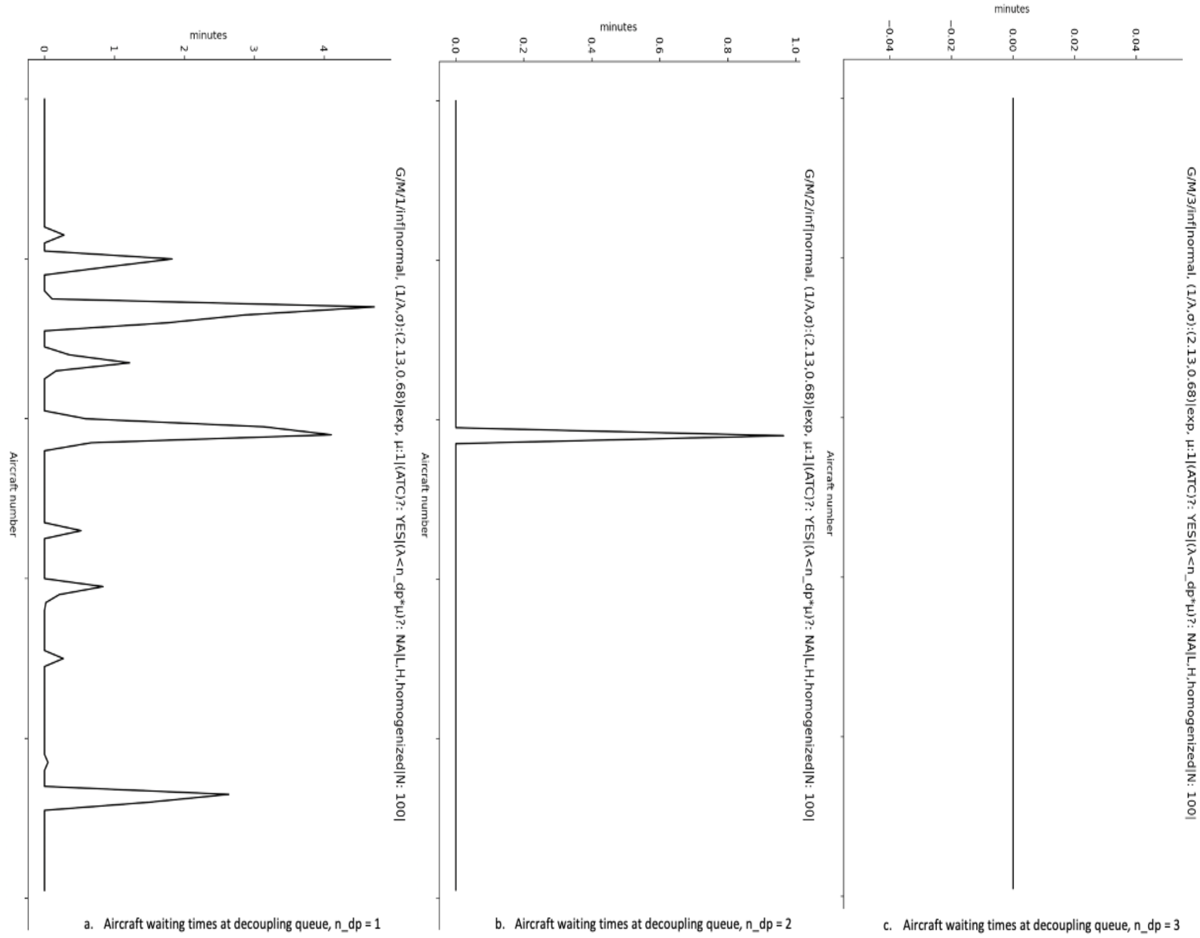


Figure 38: Aircraft waiting times at decoupling queue for N=100 aircraft arrivals and n_dp=1(a), n_dp=2(b), n_dp=3(ct) decoupling locations

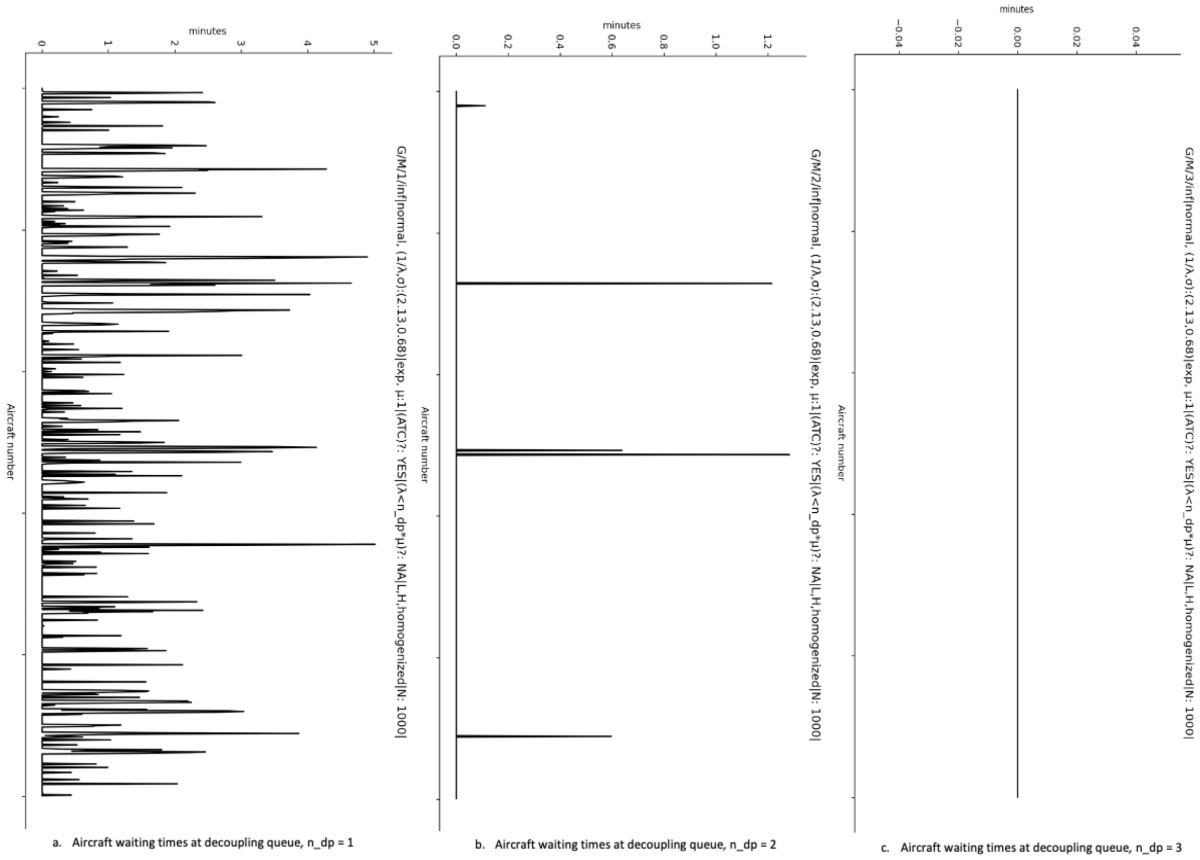


Figure 39: Aircraft waiting times at decoupling queue for N=1000 aircraft arrivals and n_dp=1 (a), n_dp=2 (b), n_dp=3 (c) decoupling locations

This is one of the scenarios where queue size is controlled easily. Even though there seems to be a high frequency of non-zero waiting times for 1000 arrivals, it does not follow a continuously increasing pattern.

We plot these for all scenarios and for the extreme scenarios where service times are much longer than interarrival times, we can observe continuously increasing waiting time trend in these types of diagrams.

3.2.5 Summary of Results for Sequential Systems

In sequential systems where there are more than one queues, such as one queue in front of the decoupling location and the second queue in front of the runway, it is more challenging to deal with increasing queue sizes compared to parallel decoupling locations. Usually, in a sequential system, when operations at one of the delay points or decoupling locations can be handled in a faster rate than aircraft arrival frequencies, queue lengths can be controlled more easily although the ideal situation is when all delay locations have more balanced release rates and all being higher than aircraft arrival rate. Because in one of the analyzed scenarios, even though the aircraft arrival rate (0.47 aircraft per minute), which corresponds to 2.13 minutes of interarrival time, is only slightly higher than the rates of two sequential delay locations (0.4 and 0.33 aircraft per minute, which correspond to 2.5 and 3.03 minutes of delay (or service) times, respectively), in the long- term queue sizes and total time spent in the system goes up to very high levels. In non-sequential systems similar scenarios can be tackled more easily. However, if these systems are unavoidable due to the delays at runway or other points, when possible, arrival rates of aircraft could be arranged accordingly such as by keeping aircraft temporarily at a feasible space and sending them to decoupling locations at a rate that they can be handled considering the slowest conflict or delay points in the queueing system. Alternatively, service times at certain decoupling locations could be improved to meet arrival rates. Building extra decoupling locations sequentially does not contribute much to dealing with queue sizes unless they are equally fast in service and have no obstacles in between.

An example of the view of a sequential system at the time of 63rd aircraft arrival during simulation is seen in Figure 40. Here *arrival rate/service rate at delay location 1/service rate at delay location 2* is 1/2/1. This means that service rate at delay location 1 is faster than service rate at delay location 2. It is also faster than aircraft arrival frequency. As a result, 63 aircraft arriving at first delay location quickly leave that location, so size of the first queue is only 1, however, 13 aircraft exist in the second queue since second delay location cannot release its entity as quickly as delay location 1. As a result, out of 63 arrivals only 47 aircraft could leave the sequential system at the time of tracking.

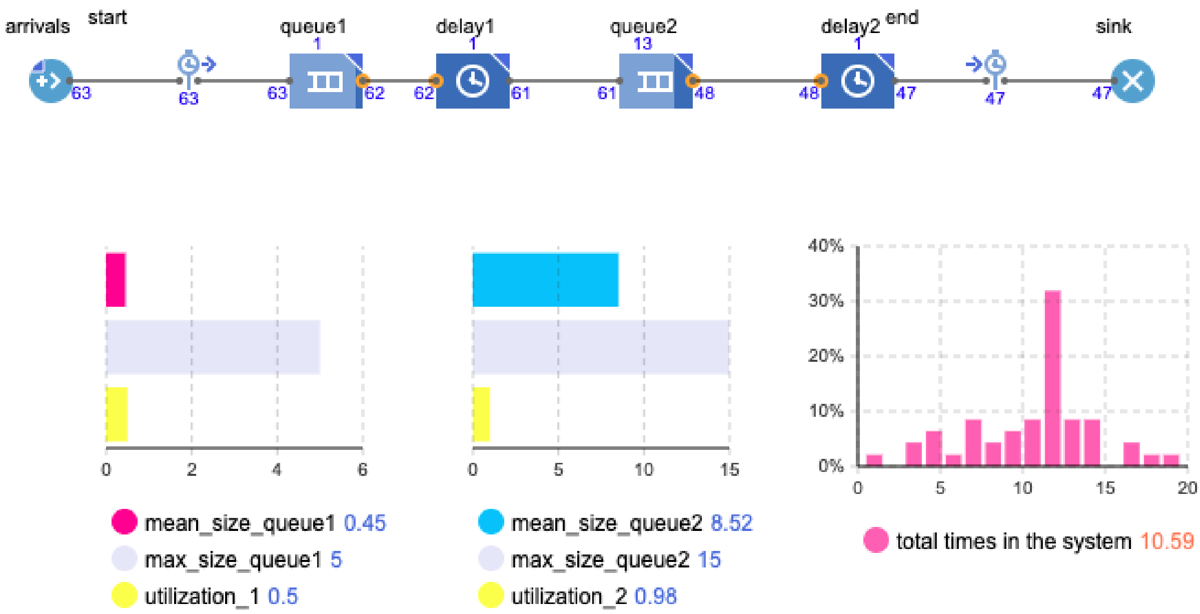


Figure 40: Two sequential queues with arrival/service1/service2 rates of 1/2/1 – simulation state at 63rd arrival

In Figure 40, it is seen that the utilization of the first delay location (delay1) for queue1 is 0.5 and the utilization of the second delay location (delay2) for queue2 is 0.98, over 63 aircraft arrivals. The reason for lower utilization of the first delay location is that the service time at first delay location is faster than the aircraft arrival rate. When a server or decoupling location is not fully utilized, the negative impact is that the airport area dedicated to decoupling remains idle and restricts the use of airspace for other operations. In the example in Figure 40, this idle time is 50% of observed time at the first delay location (delay1) and the fast service rate at this location does not improve the throughput (47 aircraft departures over 63 aircraft arrivals at the time of tracking) either since there exist a second delay location (delay2) sequentially located after the first one and serves at a slower rate. Thus, while adding new decoupling locations in sequential systems, considering the service rates and arrival rates at each delay point is critical. The ideal scenarios are where mean and max queue sizes are reasonably low and utilization is not low for each server at a sequential system. Simulations should be repeated for each potential scenario. If the throughput of the system is the same as the one after adding an additional decoupling location, or at an acceptable level already, then adding an additional decoupling location would not make sense due to the limited space at airports. On the other hand, if the additional decoupling location has a substantial impact on decreasing the queue sizes overall the system, it should be added to the existing system since the aircraft queues also occupy the airport area.

3.2.6 Summary of Results for Parallel Systems

The simulation of queues of aircraft for single and several decoupling locations in parallel infrastructure helped to gain insight on the minimum number of decoupling locations that can serve the need for various scenarios. While selecting the best number of decoupling locations to build, the goal is to reduce the queue size and waiting times as well as to avoid low utilization of allocated decoupling locations since low utilization ratios or idle times of additional decoupling locations lead to indirect costs to the airspace users.

As results, we obtained the expected waiting times in the queue/s and in the system -queues and decoupling/delay locations -, expected number of aircraft in the queue and in the system, utilization of system based on ratios of idle and busy times for each simulated scenario.

In addition to a set of preliminary tests, we simulated the arrivals of Large and Heavy aircraft based on ATC separation guidelines and safety buffers, and different frequencies of aircraft arrivals and service rates based on Markovian and General distributions. We simulated 3 ATC based scenarios with roulette wheel, poisson and normally distributed arrivals for 1 to 5 parallel decoupling locations, considering separation guidelines and safety buffers. We also simulated the more general scenarios with different frequencies of aircraft arrivals in which cases we simulated the conditions where infinite queues could still be avoided by adding one more decoupling location. Additionally, we simulated the highly slow service rates where infinite queues cannot be avoided even with 5 parallel decoupling locations and more decoupling locations are needed. We repeated simulations for each scenario with 10, 100, 1000 aircraft arrivals.

We generated the following inputs and outputs for each simulated scenario: (1) aircraft interarrival time distributions, either using ATC based roulette wheel or according to probability distributions, (2) distributions of decoupling durations, (3) simulation tables including the times aircraft enter the system, start being decoupled, leave the system, the remaining times of servers to become free, (4) simulation timelines which show when a Large or Heavy aircraft arrives at and leave the system in the case of heterogeneous arrivals or when an aircraft arrives at and leave the system in the case of homogeneous or homogenized arrivals, and keep track of the number of aircraft existing at the system until a new event occurs, (5) simulation result tables which contain numerical outputs such as expected waiting times of aircraft in the queue (Wq), expected waiting times of aircraft in the system (Ws), expected number of aircraft in the queue (Lq), expected number of aircraft in the system (Ls), and utilization (U), (6) waiting time diagrams for aircraft arrivals for different number of decoupling locations, (7) idle-occupied time ratios of the system with different number of decoupling locations, (8) utilization diagrams over different number of decoupling locations, (9) the trends of all output types that are combined in common diagrams. We evaluate the results based on these outputs.

An obvious indicator of operational performance is the maximum waiting time in the queue which shows the highest waiting time experienced in the queue and it is plotted for 1 to 5 decoupling points. While in some scenarios maximum waiting time in the queue with 1 decoupling location can be 8-10 or 1-2 minutes, in worst case scenarios it can go up to 800 minutes. These durations decrease by increasing the number of decoupling locations. In moderate cases, maximum waiting time usually reduces to 0 or highly low values for 2 or 3 decoupling locations. When maximum waiting time is reduced to 0 with 2 or 3 decoupling locations, additional ones are redundant and would be costly to keep. In worst case scenarios with infinity queues, 3 decoupling locations can also reduce the maximum waiting time almost by half compared to single decoupling location simulation. The mean waiting time is the mean waiting time in the queue over all aircraft arrivals. Reducing the mean waiting time by increasing the number of decoupling locations is easier compared to maximum waiting time, The benefit of decreasing the maximum and mean waiting time is to eliminate potential takeoff delays.

The expected number of aircraft in the queue decreases as waiting times decrease since many of the aircraft have been served and left the system or entered the decoupling point detaching from the queue in case of lower waiting times. This value decreases when the number of decoupling locations increases. Decreasing the aircraft queue length at decoupling locations is important since the aircraft queue would occupy a large space at the airport.

The probability of having 0 aircraft in the system means that the system is idle. As the number of decoupling locations increases this value increases. High value of this is an indicator that queue sizes were able to be controlled. However, it might also mean that the system is not fully utilized due to less frequent arrivals. This is not a desirable case since redundant times of allocated decoupling locations would be costly as these spaces are allocated for decoupling rather than other operations at the airport.

The utilization is an indicator of occupied states of the system and decreases by increasing number of decoupling locations. Low utilization values are not ideal since this means that allocated spaces are not frequently used and unnecessarily occupy the airport area.

In waiting time diagrams where waiting times for all aircraft are plotted for each separate scenario, it is observed that the frequency of non-zero values are generally higher in diagrams with smaller number of decoupling locations. Also, in extreme scenarios when there exists a constantly increasing trend with single decoupling location, a more stable pattern is seen with higher number of decoupling locations. The benefit of reducing waiting time for each arriving aircraft is the potential decrease in aircraft queue lengths and takeoff delay as in the case of decreasing mean and maximum waiting time.

In many of the simulated scenarios, 3 parallel decoupling locations reduced the maximum and mean waiting times in the queue and expected number of aircraft in the queue to 0 or decreased them significantly even for the worst-case scenarios where arrivals are highly frequent. With simulations for the short term i.e., with 10 arrivals, eliminating the waiting times were possible with smaller number of decoupling locations compared to longer term simulations with 100, 1000, arrivals in some cases, even though the arrival and service rates and distributions were the same. Usually, the queues with ATC based arrivals were easier to tackle since in those scenarios interarrival times were higher due to trailing restrictions. In some scenarios 2 decoupling locations could also achieve small mean waiting times although not eliminated them completely. Increasing the number of decoupling locations also increases the idle times of the system while it reduces waiting times.

While deciding on the number of decoupling locations to allocate, conflicting objectives should be considered. That is, in a case when all waiting times and queue size can be reduced to 0 by adding one more decoupling location, this could increase the idle times and lead to not fully utilizing all decoupling locations all the time. If this decreased utilization level will cause indirect costs for the airport, then decision makers could prefer to have a smaller number of decoupling locations for which waiting times would not be 0 but still acceptable and utilization is not so low.

To give an example, the decrease in utilization ratio of the system by adding additional decoupling locations for ATC based roulette wheel scenario for 1000 arrivals is shown in Figure 41. Allocating single decoupling location leads to a utilization ratio that is more than 50%, adding the second decoupling location reduces the utilization ratio to a value lower than 30%, and the third one reduces that to a value less than 20%. The decrease is significant for adding the second decoupling location. To decide on number of decoupling locations, the diagram in Figure 41 should be evaluated with the output diagram in Figure 30 which shows that highest waiting time is 8 minutes with 1 decoupling location, 1-2 minutes with 2 decoupling locations, and around 0 minutes with 3 decoupling locations. In this case, depending on the goal, allocating 2 decoupling locations with 30% utilization and 1-2 minutes waiting time in the worst case might be chosen over allocating 3 decoupling with 20% utilization with around 0 minutes waiting time in the worst case, since utilization is important to avoid idle time costs. The mean waiting time with 1 decoupling location is shown as between 0 and 1 minutes in Figure 30. Considering the high utilization ratio with 1 decoupling location and taking the mean waiting time as a decision factor instead of the maximum waiting time, even the single decoupling location might satisfy the need in this case depending on the decision strategy and the costs caused by waiting times versus idle times.

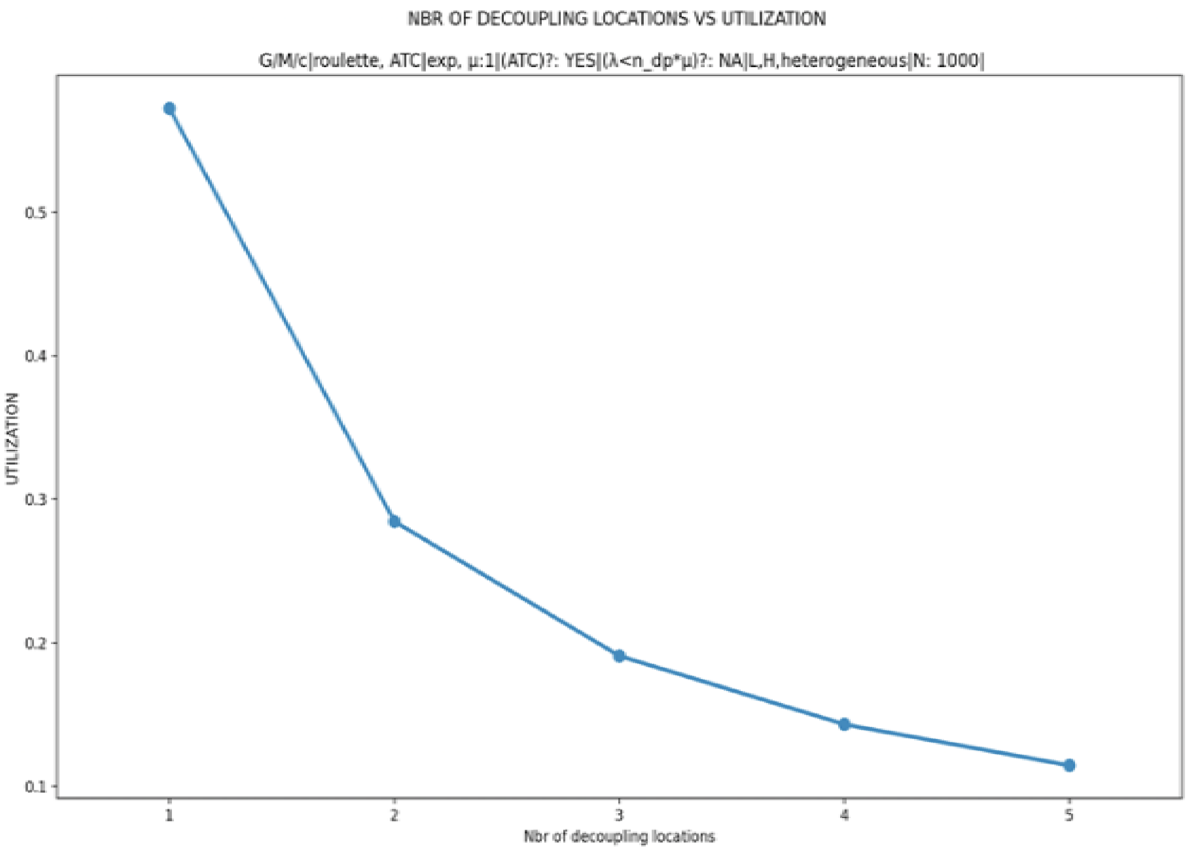


Figure 41: Number of decoupling locations versus utilization for ATC based roulette wheel scenario

In ATC based scenarios due to the speed limits and safety buffers, arrival rates of aircraft tend to be lower than service rates at decoupling locations, so decoupling operations can be completed faster than the subsequent arrivals and queue sizes can be controlled rather easily. The positive outputs related to ATC based roulette wheel scenario in Figure 41 and Figure 30 reflect these facts.

Certain ratios of arrival to service rates and related distributions are crucial factors that cause a queue to go to infinity or follow a more stable pattern. For the scenarios which are not ATC based but rather stable compared to highly slow service rates, several decoupling locations would be preferable instead of single decoupling location. On the other hand, highly slow service rate scenarios result in queue sizes going to infinity even with 5 decoupling locations. In such scenarios, if it is not possible to increase the service rates at decoupling locations or decrease the arrival frequency, then having to allocate additional decoupling locations is unavoidable.

In this study we have attempted to evaluate various scenarios including extreme cases. ATC based scenarios are more likely to reflect the real cases and rather manageable compared to other scenarios due to the simulation outputs.

The locations where decoupling points are built might affect the simulation results. In parallel system scenarios we simulated the cases where decoupling locations are in front of the runways. In this case the length of the path the aircraft takes to the runway does not increase much but the costs stem from creating new queueing areas in front of decoupling locations. Unless these queueing areas are managed or designed wisely, the flow of process at the airport would be disrupted and create extra costs due to the disruptions caused by additional decoupling locations and related queueing areas. In other cases where there are not enough spaces in front of the runways, adding decoupling locations might increase the path to the runway and the travel time from decoupling location to runway and these should also be considered in evaluations.

3.2.7 Impact on Airport Layout

Establishment of decoupling points at airports would have an impact on airport layout. The level of impact depends on the existing infrastructure of the airport. The closer a decoupling point to a runway the more the cost saving regarding the path to runway from decoupling location is. Decoupling points can be established on taxiways or in front of the runways. Also, taxibots would need to return to parking locations after decoupling. The capacity or size of the airport is crucial for determination of the locations on existing layout to allocate new spaces. Allocating a limited number of decoupling locations in front of the runways might increase delays in takeoff due to the decoupling process. Thus, allocating alternative points in parallel improves the flow of operations. Some airports (such as CDG) might have enough space in front of the runway/s for building parallel decoupling locations, in their existing layouts. In such cases, the impact on layout would not be huge. If there is not enough space for building parallel decoupling locations in front of the runway but still one or two decoupling points can be allocated, then aircraft queue at decoupling locations might increase and more space might be needed for the queueing area. Alternatively, decoupling locations might be built on taxiways if there is no space close to the runways which will increase the cost to reach to runway after decoupling.

3.2.8 Conclusion

We have simulated and analyzed the options of building parallel and sequential systems for handling decoupling operations.

For parallel decoupling locations, in many of the simulated scenarios, 3 decoupling locations either decrease the waiting times and queue sizes to 0 or to a value close to 0. In extreme scenarios with frequent arrivals and highly slow service times, expected waiting time in the queue with 3 decoupling locations is lower than expected waiting time with 1 decoupling location. For example, for 10 arrivals with such a scenario, expected waiting time of 25.237 minutes (c.a. 25 minutes) with 1 decoupling location, reduces to 3.136 minutes (c.a. 3 minutes) with 3 decoupling locations, 1.223 (c.a. 1 minute) minutes with 4 decoupling locations and 0.016 (c.a. 0 minute) minutes with 5 decoupling locations. Usually, the decrease trend is sharp until 3 decoupling locations and tends to lose pace after 3. Another scenario which is not an extreme case, but it is known that it can be properly handled by 4 decoupling locations, a significant decrease with 3 decoupling locations is still observed, i.e., for 1000 arrivals, 374.36 (c.a. 374) minutes of expected waiting time with 1 decoupling location reduces to 17.489 (c.a. 17) minutes with 3 decoupling locations, and to 0.774 minutes with 4 decoupling locations. For some cases with less frequent arrivals, even 2 decoupling locations were able to reduce the expected waiting time to 0 or to a value close to 0.

For ATC based scenarios, we simulated different scenarios where (1) aircraft arrivals conform to Poisson distribution with a rate derived by finding a mean interarrival time using the transition probabilities of large and heavy aircraft and trailing speeds based on ATC guidelines, (2) aircraft arrivals are normally distributed with ATC based interarrival mean as in (1) and a standard deviation obtained regarding ATC rules, (3) different types of aircraft arrivals are created by roulette wheel selection considering their arrival probabilities and interarrival times are exactly set according to ATC guidelines for each leading-trailing aircraft type pair. In these scenarios, although queue behaviors were slightly different due to the different arrival distributions, for all of them, queue sizes could be reduced to 0 by 2-3 decoupling locations. Also, with 1-2 decoupling locations queue sizes and waiting times were not high. For roulette wheel-based arrivals results were better than ATC based Poisson and ATC based normally distributed arrivals, because while for roulette wheel interarrival times were more frequent between 1 and 2 minutes and mostly larger than 1 minute, in other cases the number of the interarrival times that are closer to 0 or 1 were higher than the ones in roulette wheel. Therefore, with roulette wheel arrival frequency tended to be less frequent and queue size was tackled more easily.

For general scenarios, we analyzed the cases with different ratios of arrival to service rates to see the behaviors of queues with more and less frequent arrivals compared to service rates. Note that the findings related to these scenarios are only valid for poisson arrivals and exponentially distributed service times and cannot be generalized. In these scenarios we gradually increased the arrival rates and at every increase we broke the steady state condition for one more decoupling location. That is while in one scenario arrival rate was higher than the total of service rates of 2 decoupling locations but smaller than the total of service rates of 3 or more, in another scenario, arrival rate was higher than total of service rates of 4 decoupling locations but smaller than others, and this continued up to 5 decoupling locations. According to these results in the situation when arrival rate is higher than the service rate of single decoupling location but smaller than the total of two, then by building two decoupling locations waiting times and queue sizes can be significantly reduced. When the arrival rate becomes higher, equal or more than three service rates, then we need 4 decoupling locations to deal with the queue better. With the violation of steady state rules for higher number of queues it becomes more challenging. For example, if arrival rate is more than a total of service times of 4 decoupling locations, but less than 5, more than 40 minutes of waiting times in the queue for 1 decoupling location over 100 arrivals were observed, and they could be reduced to c.a. 1 minute only after adding the fifth decoupling location. However, by allocating 3 decoupling locations 7 minutes of mean waiting time can be achieved too.

We also analyzed a scenario with very slow decoupling service compared to interarrival times. To design this scenario, we created Poisson arrivals with a rate of 1.5 aircraft per minute and exponentially distributed decoupling durations with rate 1/6 per minute such that interarrival times are most likely to be ranging from 0 to 6 minutes and having higher values such as 15 or 20 minutes occasionally. In this case, queue size tends to go to infinity even with five decoupling locations for long term simulation runs. Even for this extreme scenario, which is unlikely to exist, adding the third decoupling location decreases the mean waiting time and maximum waiting time in the queue by more than half of the mean and maximum waiting times obtained with 1 decoupling locations.

We have also analyzed the sequential systems with two delay locations. Dealing with these cases is challenging since more than one queue occurs and lower service rate at one location prevents the quick release of aircraft from the system even though service rate at another location is higher.

To summarize, parallel systems are better than sequential systems.In parallel systems, when arrival and service rates are more balanced, allocating 2 decoupling locations reduced the waiting times in the queue and expected number of aircraft in the queue significantly. Moreover, allocating 3 parallel decoupling locations eliminated all waiting times in the queue in many of the simulated scenarios. For the parallel system scenarios, (except for the scenarios with highly slow service rates), service rates and distributions are kept the same to see the impact of different arrival scenarios. Consequently, for simulated service rates, ATC based scenarios had more balanced queueing systems, since approach restrictions of ATC slow down arrival frequencies compared to other simulated scenarios. As a result, in ATC-based scenarios, queue sizes and delays were handled easily by fewer decoupling locations compared to other scenarios. By increasing the number of decoupling locations, utilization or the ratio of idle times of the system increases. Therefore, the number of decoupling locations could be decided upon considering different criteria such as utilization, its effect on mean queue size and waiting times. In reality, available space, the cost of infrastructure and building permits/restrictions will also influence this decision.

The number and arrangement of decoupling locations is important for improving the benefits and costs of operations regarding the use of taxibots. A cost benefit analysis regarding the new layout and number of allocated spaces must be taken into consideration at strategical level before changing existing processes and layouts for taxibot operations. Building decoupling points close to runways will increase the benefit of taxibot since it will decrease the traveling cost of aircraft after being decoupled to reach to runway. Furthermore, building alternative decoupling locations that do not block each other, in other words in parallel, close to runway, will reduce queue size at decoupling area and increase the benefit of new taxibot process by saving space required to handle the decoupling operations, in queueing area. Building decoupling points at other locations would increase the costs of adopting the taxibot system compared to decoupling closer to runway, although it would still have more benefit compared to not adopting the taxibot system. Having to build sequential decoupling points due to the restricted space will also increase aircraft queues and required queueing spaces which would lead to excessive waiting times and costs related to takeoff delays. Thus, the layout design and solving an allocation problem is highly important and the best solution might be different for each airport depending on its complexity, number of runways, distribution of fleet size, distance between the gates and runway. An optimal allocation of decoupling locations might be found out by considering fuel costs of using taxibots until decoupling locations and the traveling costs of aircraft without using taxibots after being decoupled, which will also depend on the distance between the apron and the potential decoupling locations and the distance from these decoupling locations to runways. Also, the variety of sizes of fleet affect the speed of movements. Furthermore, if there is a limited number of taxibots and several runways, optimal usage of taxibot resources is important and consideration must be given to the impact of distance between decoupling and parking locations of taxibots and the runways. Thus, a highly complex network problem occurs depending on airport complexity, to find out the best solution in terms of costs and benefits of alternative allocations. Considering all these factors, simulations that we propose in this section can be repeated at a deeper level with the adaptations related to available locations for potential decoupling points, distances between the gates, runways, and allowed locations for decoupling, related fuel costs for taxibot operations, alternative taxiways, for specific airports.

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4 Cost benefit analysis for autonomous eTaxi

For autonomous eTaxi the main benefit is the fuel saved during taxi, for which large airports with longest taxi times show the largest benefit. The main costs are the costs of installing the system on an aircraft, as well as increased fuel consumption in flight due to the additional weight of the electric motors and the rest of the system. This increased fuel consumption will increase with increased flight distances. The eTaxi system is thus expected to be most beneficial on shorter flights between large airports, provided aircraft are not towed there.

To have a best case the eTaxi system was assumed to be able to move the aircraft at sufficient speed without any engines running to not cause significant delays and congestion on the taxiways, which is one of the main concerns with the currently proposed solutions. If engines where running, as proposed for the wheeltug system, this would not have any additional economic benefit over normal single engine taxying.

For the savings for installing an eTaxi system, the same values were used for the impact per airport as for towing, however the values for high power APU usage where used.

Additionally, a fuel penalty during cruise for the added weight was used, which was calculated based on the Breguet range equation. The total fuel is then the fuel saving during taxi minus the extra fuel consumption during cruise.

The main hypothesis is thus that eTaxi will mainly be beneficial on short range flights between airports with long taxi times, where the extra fuel burn during cruise is limited and the savings during taxying are large.

$$R = C \ln \frac{W_{TO}}{W_{TO} - W_{Fuel}}$$

Where R [km] is the range, C [km] is the aircraft specific range parameter, which is an indication of the aerodynamic and propulsive efficiency of the aircraft. W_{TO} [kg] is the take-off weight and W_{fuel} [kg] is the fuel weight.

From the equation above we can deduce that the fuel required increases with respect to the added weight according to the following equation, and the additional fuel consumption is thus independent of the actual take-off weight or fuel load and only depends on the range and the range parameter:

$$\frac{dW_{Fuel}}{dW_{TO}} = 1 - e^{-\frac{R}{C}}$$

These four representative aircraft were used to represent all aircraft in the flight schedule and the values are shown in table 21. The weight assumed for the ETS is a very rough estimation, as no flightworthy device is available yet and the total weight, including modifications to the APU and electrical system, is unknown.

Table 21: Representative aircraft range and ETS weight values

Aircraft	Range parameter C [km]	Added weight by eTaxi device [kg]
E190	21156	500
B738	19103	500
A320	23640	500
A350	32650	1000

Together with ICAO emissions data assuming climb thrust values for the cruise fuel consumption and the changes to taxi in and out fuel emissions and fuel consumption, a total impact of equipping an aircraft with an eTaxi device is calculated for each flight on each route, a few examples are shown in table 22. It should be noted that some KPIs (most notably NO_x) increases overall due to the added weight in cruise.

Table 22: Representative aircraft distance and ETS weight values compared to normal taxi and single engine taxi

Orig	Dest	AC	Distance [km]	Cruise fuel increase [kg]	Taxi Out fuel [kg]	Taxi In fuel [kg]	Total Fuel [kg]	Fuel SET [kg]
AMS	MXP	B738	797	20	-108	-43	-130	-52
AMS	MXP	A320	797	17	-98	-39	-120	-49
AMS	LHR	B738	370	10	-108	-72	-170	-61
AMS	LHR	E190	370	9	-81	-54	-127	-49
AMS	JFK	A350	5848	164	-287	-409	-532	-225

This data is then used in a which optimizes the flow of aircraft equipped with ETS through an airlines day schedule and used a fixed (marginal) cost for using ETS equipped aircraft per day. The model does not track the number of non-equipped aircraft nor the individual aircraft.

4.1 eTaxi fleet assignment model

4.1.1 Variables:

z_F : Total fuel savings

z_V : Total marginal fuel savings per eTaxi equipped aircraft

$y_{a,v,t}$: Number of equipped aircraft type v stationed at airport a at time t (int)

x_o: Operation o is flown by eTaxi equipped aircraft (binary)

4.1.2 Sets:

O: Operations (flights)

$O^{dep}_{v,a,t}$: Departures from airport a with aircraft type v at time t

$O^{arr}_{v,a,t}$: Arrivals at airport a with aircraft type v between time t-1 and t

V: Aircraft types

A_v: Airports visited by aircraft type v

$T_{v,a}$: Departure times of type v from airport a

4.1.3 Parameters:

C_V: Marginal cost per eTaxi equipped aircraft

$C_{F,o}$: Fuel saving per operation (if equipped with eTaxi)

4.1.4 Objectives

The total objective is the fuel saved z_F minus the marginal cost z_V in kilograms of fuel of equipping the aircraft.

Maximize $Z = z_F - z_V$

$$z_V = \sum_{a \in A_v, v \in V} y_{a,v,0}$$

$$z_F = \sum_{o \in O} C_{F,o} x_o$$

4.1.5 Constraints

This model uses only a single constraint. At each time interval, the number of departing aircraft and aircraft remaining on the ground must be equal to the number of arriving aircraft and the aircraft that remained from the previous interval

$$\sum_{o \in O^{arr}_{v,a,t}} x_o - \sum_{o \in O^{dep}_{v,a,t}} x_o + y_{a,v,t-1} - y_{a,v,t} = 0, t \in T_{v,a} \cup a \in A_v \cup v \in V$$

4.2 Overall results

Table 23 shows the results for a very low marginal cost of 10 kg of fuel per equipped aircraft and illustrates the total savings if all aircraft where equipped. Note that while fuel and CO_2 emissions are always reduced, especially NO_x emissions increase due to the added weight in flight.

Table 24 shows that if the installation of the system on an aircraft needs to be compensated by at least 1000kg of fuel on a peak day this will result in a significantly reduced number of aircraft equipped, only about 10%. The business case for eTaxi thus seems significantly less strong than that for towing.

Table 25 shows the impact of using single engine taxiing on all flights of the respective airlines. Implementing SET on all flights will result in 40-50% of the savings for eTaxi, limiting the added value for eTaxi on top of SET to 50-60%.

Figure 42 indicates that there is indeed a slight increase in the average taxi times when the marginal cost per installed eTaxi device increases, indicating that the flights are concentrated on larger and more busy airports when the marginal cost per installed eTaxi device increases. Figure 43 shows that the average flow distance decreases significantly with increased marginal cost per installed eTaxi device. This enforces the hypothesis that eTaxi will mainly be beneficial on short range flights between airports with long taxi times. Finally, there is an overlap with airports likely to deploy towing and airports visited by autonomous eTaxi equipped aircraft, which is shown in in Table 26. If towing is implemented at these airports, autonomous eTaxi is not likely to have any benefit.

Table 23: Fuel and emission impact for a marginal fuel costs of 10 kg of fuel per installed eTaxi device

Code	Name	Type	Equipped AC	Fuel [tons]	CO2 [tons]	CO [g]	HC [g]	NOx [kg]
U2	Easyjet	A320	338	-192.7	-608.9	-2977	238.6	642.9
FR	Ryanair	B738	316	-136.9	-432.7	262	450.1	670.6
LH	Lufthansa	A320	166	-117.9	-372.7	-2543	39.0	289.5
VY	Vueling	A320	128	-84.8	-268.0	-1639	56.1	235.4
BA	British Airways	A320	90	-58.5	-184.8	-1199	26.9	150.2
AF	Air France	A320	85	-58.8	-185.9	-1192	30.4	154.9
EW	Eurowings	A320	108	-57.2	-180.8	-994	55.7	176.7
AZ	Alitalia	A320	64	-50.3	-158.9	-1215	-2.9	104.4
W6	Wizz Air	A320	111	-42.7	-135.1	122	168.9	255.3
IB	Iberia	A320	52	-39.2	-123.8	-767	23.6	106.1
Total			**1458**	**-839**	**-2651.7**	**-12143**	**1087**	**2786**
Yearly	**80% utilization**			**-245029**	**-774291**	**-3545828**	**317271**	**813523**

Table 24: Fuel and emission impact for a marginal fuel costs of 1000 kg of fuel per installed eTaxi device

Code	Name	Type	Equipped AC	Fuel [tons]	CO2 [tons]	CO [g]	HC [g]	NOx [kg]
U2	Easyjet	A320	36	-42.6	-134.6	-1144	-19.4	72.0
FR	Ryanair	B738	23	-29.4	-93.0	-652	0.1	49.3
LH	Lufthansa	A320	44	-55.3	-174.9	-1551	-34.3	84.8
VY	Vueling	A320	22	-30.1	-95.2	-835	-17.6	47.2
BA	British Airways	A320	15	-18.2	-57.4	-525	-14.2	24.8
AF	Air France	A320	14	-17.0	-53.9	-452	-7.2	29.3
EW	Eurowings	A320	6	-6.6	-20.9	-187	-4.3	9.9
AZ	Alitalia	A320	20	-25.4	-80.3	-708	-15.4	39.2
W6	Wizz Air	A320						
IB	Iberia	A320	12	-17.1	-54.0	-487	-12.1	24.6
Total			**192**	**-242**	**-764**	**-6542**	**-124**	**381**
Yearly	**80% utilization**			**-70600**	**-223097**	**-1910138**	**-36320**	**111268**

Table 25: Fuel and emission impact for single engine taxi per airline

Code	Name	Type	Fuel [tons]	CO2 [tons]	CO [g]	HC [g]	NOx [kg]
U2	Easyjet	A320	-84.7	-267.6	-6377	-400	231
FR	Ryanair	B738	-65.2	-206.4	-4523	-247	179
LH	Lufthansa	A320	-50.2	-158.2	-3771	-237	136
VY	Vueling	A320	-35.8	-113.1	-2695	-169	98
BA	British Airways	A320	-26.0	-81.4	-1939	-122	70
AF	Air France	A320	-25.8	-81.5	-1943	-122	70

EW	Eurowings	A320	-25.6	-80.7	-1924	-121	70
AZ	Alitalia	A320	-21.2	-67.2	-1602	-101	58
W6	Wizz Air	A320	-21.5	-68.0	-1622	-102	59
IB	Iberia	A320	-17.1	-54.1	-1290	-81	47
Total			-373.0	-1178.3	-27686.9	-1699.8	1016.7
Yearly	**80% utilization**		-108927	-344063	-8084561	-496340	296890

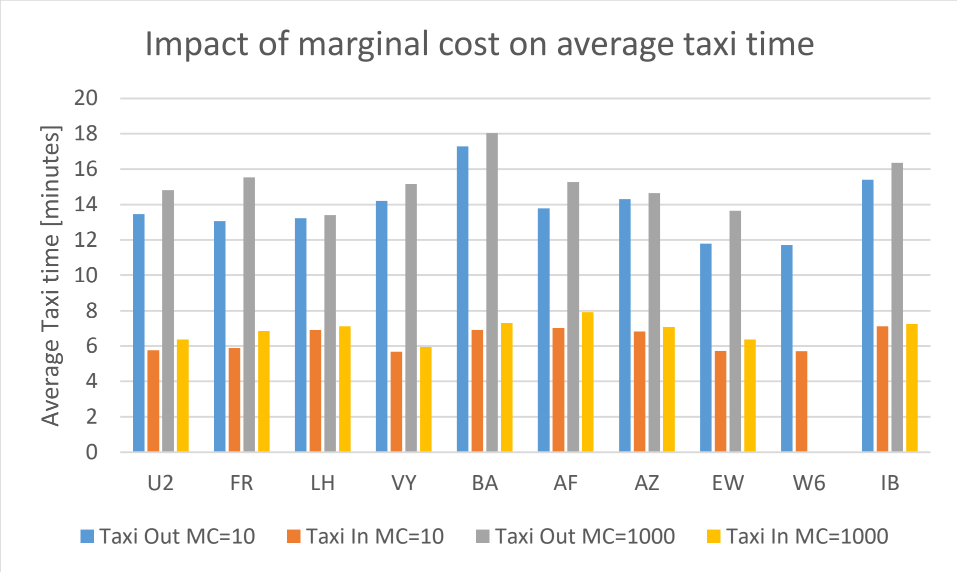

Figure 42: Impact of marginal costs on average taxi times per airline

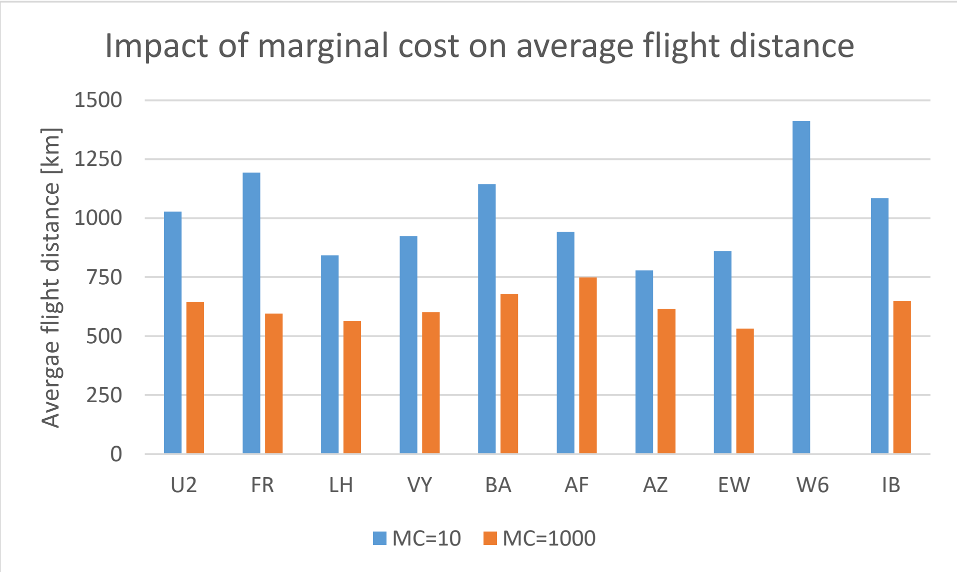

Figure 43: Impact of marginal costs on average flown distance per airline

Table 26: Top 10 airports with number of departures for a 1000 kg marginal eTaxi cost scenario for the top 10 airlines

Airport	Departures	Percentage	Taxi In (min)	Taxi Out (min)
BCN	141	8.40%	5.4	18.1
FRA	138	8.20%	9.2	14.3
FCO	129	7.70%	9.1	17.3
CDG	105	6.20%	9.5	16.3
MUC	105	6.20%	5.8	13.1
MAD	89	5.30%	8.9	18.2

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LGW	73	4.30%	7.1	21.4
LHR	73	4.30%	8.6	22.3
TXL	41	2.40%	5.3	10.4
AMS	40	2.40%	8.0	13.9
Total	973	55.50%		

4.3 Sensitivity analysis of implementing eTaxi for KLM

Finally, figures 42 and 43 show the impact of the weight of the ETS system and the marginal cost per installation for KLM 737 aircraft. As can be seen, both have a highly diminishing effect on the overall fuel and thus emissions savings. The installation cost should be recoverable with a 500 kg fuel savings per day and the weight should be as low as possible.

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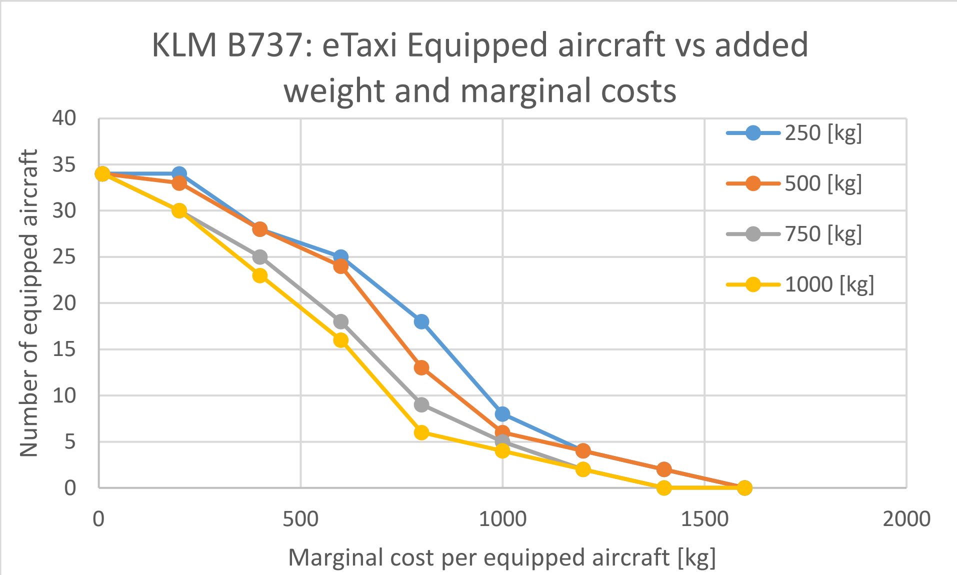

Figure 44: Impact of weight and marginal cost on the number of KLM 737 aircraft equipped

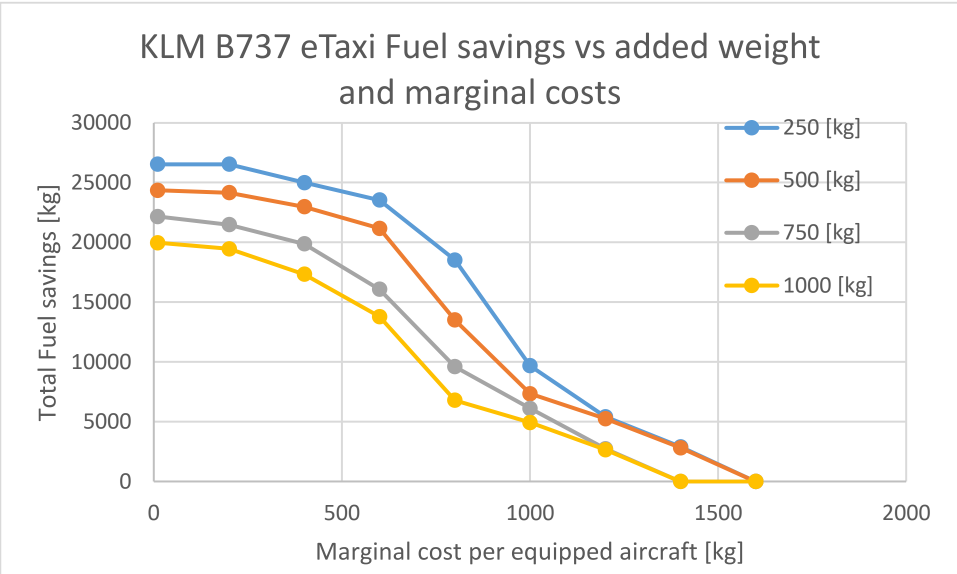

Figure 45 : Impact of weight and marginal cost on fuel savings per peak day on KLM 737 aircraft

5 Conclusions and recommendations

It was the intention of this work to give a relatively high-level overview of the most important potential costs and benefits of implementing operational towing and autonomous eTaxi. No specific conclusions on applicability of these solutions should be made only on this document and it should only be seen as a starting point for further research.

The analysis indicated that for 13 larger European airports there seems to a reasonable business case to implement towing, assuming each towing vehicle needs to offset an average of 1000 kg of fuel on a peak day. More specific research should be done at each airport with a more accurate schedule and specific taxi times before further implementation.

Further analysis for Amsterdam Airport Schiphol (AMS) and Paris CDG shows that towing all heavy and medium sized aircraft vehicles based on a 2018 peak day schedule seems to make most sense. For smaller, regional aircraft, utilization would be relatively low, limiting the business case for these aircraft. It could make sense to only operate a few of these smaller towing vehicles and accept that not all aircraft can always be towed.

For eTaxi without any engines on, the business model shows net savings if installed on all aircraft. If we would need at least 1000kg of fuel saved per day to offset the installations costs, only around 10% of the fleet would be equipped. Sensitivity analysis shows that the weight added must also be very limited, which could be a challenge.

The business model thus seems a lot more limited than that for towing, especially as towing aircraft equipped with an eTaxi system instead of using the eTaxi system would completely negate the benefit of the eTaxi system, as the main benefit in terms of on ground fuel consumption is largely at the same large airports as towing would be most beneficial.

5.1 Recommendations

Only a single peak day in 2018 was examined in this research. Especially if aircraft have a flight schedule very dependent on the season, this might not always be representative. More representative schedules for a wide range of days could be used to get more representative results.

For towing the most important unknown is the operating cost of a towing vehicle, which can only be quantified by the manufacturer and the operator. To limit the operational costs, it would be beneficial to make the towing vehicles autonomous and not require a driver on board. This would also limit staffing issues.

Adding ground power for the aircraft and possibly pre-conditioned air and an air starter unit to the towing vehicle would reduce the usage of the APU on the ground and thus increase the fuel savings.

During operation, some values should be monitored, including maintenance impact, engine warm up time and engine cool down time to determine more realistic costs and benefits and update the business case.

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For eTaxi, the largest unknowns are the maximum speed, total added weight of the installed system and the costs of installation. Before any meaningful decision can be made on implementation of this system, these need to be specified by the manufacturer.

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