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Agent-based Safety Modelling and Simulation of Controlling Two Airports from One Remote Tower

TU Delft

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By

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Summary

Remote tower allows the provision of air traffic control to one or more aerodromes from a location that is different than the local tower. As such, the air traffic controller or flight information officer is not required to be in the physical aerodrome tower anymore.

There are three types of remote tower operations. First, single remote tower is providing remote tower service to one aerodrome. Second, contingency remote tower is providing only continency air traffic control. Third, multiple remote tower is providing remote tower service to two or more aerodromes.

Single remote tower and contingency remote tower have been validated and are currently operational. Multiple remote tower is not operational, therefore a topic of research regarding its feasibility.

Currently, there is no available model looking into multiple remote tower operations. Developing an agent-based model can provide additional insight into the feasibility of this new concept of air traffic operations. It can be also be utilised in safety cases to assess the safety level of multiple remote tower operations.

The focus of the MSc. Thesis is to develop an agent-based model for the evaluation of multiple remote tower in Shannon and Cork Airport from one remote tower location in Dublin Airport.

The MSc. Thesis is structured following the steps of a safety risk assessments as presented in the AE4448 Agent Based Safety Risk Analysis Course.

Chapter 2 presents the acquisition of the information through desk research. The purpose of the research is acquiring knowledge and understanding of the remote tower operations, to contribute to the refinement and definition of the scenario for the agent-based model. The results and outcomes of this research step are recorded in the literature study.

Next, in chapter 3, the concept of operation for the multiple remote tower, and an overview of the current operations in Shannon and Cork are presented. Understanding the operational environment and the concept of operations represents the foundation for the hazard identification process.

Chapter 4 presents hazard identification and initial assessment for multiple remote tower operations. The aim of this step is to identify and select hazard(s) for further analysis and modelling. The hazards chosen for further analysis is Hazard 3a Instruction to correct aircraft on the other airport's frequency and Hazard 3b Incorrect instruction (different than intended) given on wrong frequency (another airport than intended).

In Chapter 5, a scenario for Hazard 3a and Hazard 3b is constructed. The purpose of this activity is to deduct a scenario where these hazards are expected to have the worst consequences, if encountered.

Next an agent-based model is developed. Chapter 6 provides the description of the agent-based model for multiple remote tower, with an overview of the relevant agents. Multi-agent Situation Awareness (MASA) is also presented.

Chapter 7 describes the petri net model for multiple remote tower, followed by the MATLAB implementation strategy. Details on the petri net model are presented in Appendix E of the MSc. Thesis.

Chapter 8 details the MC scenario being simulated, the MC simulation results overview and analysis.

In Chapter 9, an analysis of the runway incursion and the other non-nominal events against safety criteria is performed. The objective of the analysis is to determine whether the risk associated with these events is acceptable.

Chapter 10 presents the identification of bottlenecks for multiple remote tower operations.

Chapter 11 provides the outcomes of brainstorming activities with subject matter experts (SMEs) for possible improvement for multiple remote tower operations, by addressing the bottlenecks identified in the MC simulation.

Finally, Chapter 12 presents the conclusion of the MSc. Thesis, Chapter 13 presents the references used in the MSc. Thesis followed by the appendices. Appendices A and B provide further information about Shannon and Cork airport respectively. Appendix C contains the notes from hazard identification and initial analysis. Appendix D contain a list of hazards from SESAR safety assessment of remote tower operations. Appendix E contains the SDCPN Specification of Agent-Based Model for Multiple Remote Tower.

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List of Acronyms

AFIS	Aerodrome Flight Information Service
AFISO	Aerodrome Flight Information Service Officer
AMAN	Arrival Manager
AMC	Air Movements Control
ANSP	Air Navigation Service Provider
APP	Approach Control
ART	Advanced Remote Tower
A-SMGCS	Advanced Surface Movement Guidance and Control System
ATC	Air Traffic Control
ATCO	Air Traffic Control Officer
ATM	Air Traffic Management
ATS	Air Traffic Services
CONOPS	Concept of Operation
CWP	Controller working position
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DMAN	Departure Manager
DSNA	Direction des Services de la Navigation Aérienne
EASA	European Aviation Safety Agency
EFS	Electronic Flight Strip
EICK	Cork Airport
EINN	Shannon Airport
EU	European Union
EUROCAE	European Organisation for Civil Aviation Equipment
EUROCONTROL	European Organisation for the Safety of Air Navigation
FAA	Federal Aviation Administration
HD	High-Definition
HET	Human Error Template
HMI	Human Machine Interface
HTA	Hierarchical Task Analysis
IAA	Irish Aviation Authority
ICAO	International Civil Aviation Authority
IFR	Instrument Flight Rules
IPN	Interconnecting Petri Net
ISA	Instantaneous Self-Assessment
LFV	Luftfartsverket
LPN	Local Petri Net
LVP	Low Visibility Procedures
MASA	Multi-Agent Situation Awareness
MASO	Multiple Airport Simultaneous Operations
MASPS	Minimum Aviation System Performance Specification
MC	Monte Carlo
MRTO	Multiple Remote Tower

NASA	National Aeronautics and Space Administration
OSED	Operational Services and Environment Description
OTW	Out-the-Window
PANS-ATM	Procedures for Air Navigation Services- Air Traffic Management
PN	Petri Net
PTZ	Pan Tilt Zoom
RACOON	Remote Airport Concept of Operation
RCT	Remote Contingency Tower
RE	Resilience Engineering
RIMCAS	Runway Incursion Monitoring and Collision Avoidance System
ROT	Remotely Operated Tower
RT	Radio Telephony (frequency)
RTC	Remote Tower Centre
RTM	Remote Tower Module
RVT	Remote and Virtual Tower
RWY	Runway
SA	Situation Awareness
SDCPN	Stochastically and Dynamically Coloured Petri Net
SESAR	Single European Sky ATM Research
SJU	SESAR Joint Undertaking
SMART	SMART Criteria: Specific, Measurable, Achievable, Realistic, Time-Bound
SMC	Surface Movements Control
SME	Subject Matter Experts
SMGCS	Surface Movements Guidance and Control System
SMR	Surface Movement Radar
STATFOR	Eurocontrol Statics and Forecast
TLX	Task Load Index
TWR	Tower
VFR	Visual Flight Rules
WP	Work Package

Glossary of terms

Remote Tower is where air traffic control is remotely provided using direct visual capture and visual reproduction e.g. with cameras.

CWP (Controller Working Position) is the operator (ATCO) workstation including necessary ATS systems.

Remote Tower Module (RTM) is the term for the complete module including both the CWP(s) and the Visual Reproduction display screens.

A Remote Tower Centre (RTC) is a building where air traffic control is provided to one or more aerodromes. It usually includes several RTMs (or only one, if that single Remote Tower Module (RTM) enables ATS to more than one aerodrome).

A Remote Contingency Tower (RCT) is a facility used to provide remote air traffic control, including a visual reproduction, to an aerodrome in contingency situations.

1. Introduction

Air traffic control (ATC) was introduced in the 1920s at Croydon airport in the UK (CAS Membership Society Historic Croydon Airport Trust, 2017). Since then, the provision of air traffic control has been changing slowly, with few improvements made throughout the years (European Organisation for the Safety of Air Navigation (EUROCONTROL), 2013). As a result, the current European ATC system is not efficient, with shortcomings accounting for €4 billion annually (SESAR Joint Undertaking, 2009).

Supporting further ATM development, the remote tower concept is challenging the aviation industry, forcing a rethink of what we consider air traffic control.

Remote tower allows the provision of air traffic control from a facility at a distance from the airport. As such, the air traffic controller doesn't have to be in a physical tower in the aerodrome.

Remote tower can be used in multiple situations. First, it can be used at aerodromes where the traffic volume is not enough to financially sustain a manned tower. Costs can be saved from centralising resources, as well as standardising equipment and training. Next, remote tower can be implemented in aerodromes where the current tower is no longer adequate, i.e. the tower is not safe (the tower building structure is not safe) or the tower location is not allowing a full view of the airport (e.g. new airport infrastructure such as a new runway might not be visible from the tower). Finally, remote tower can also be used as a contingency solution, in either a planned (e.g. temporary work in the tower) or unplanned situation (e.g. malfunctions in the tower).

The change that comes with moving the provision of the ATC to a remote location is that there is no more *"out-of-the-window"* (OTW) view (International Civil Aviation Authority, 2016). Since the air traffic service is meant to remain unchanged, remote tower needs to remain compliant with the ICAO regulation related to the provision of a *"a continuous watch on all flight operations on and in the vicinity of an aerodrome as well as vehicles and personnel on the manoeuvring area"* (International Civil Aviation Authority, 2016), which *"shall be maintained by visual observation"* (International Civil Aviation Authority, 2016).

To continue visual surveillance without access to an OTW view, the most straightforward solution is employing cameras and screens. ICAO states that *"In the absence of visual observation of all or part of the manoeuvring area or to supplement visual observation, surface movement radar (SMR) provided in accordance with the provisions of Annex 14, Volume I, or other suitable surveillance equipment, should be utilized to:*

a) monitor the movement of aircraft and vehicles on the manoeuvring area;

b) provide directional information to pilots and vehicle drivers as necessary; and

c) provide advice and assistance for the safe and efficient movement of aircraft and vehicles on the manoeuvring area" (International Civil Aviation Authority , 2001)".

At a basic level, remote tower may just replicate the traditional tower view. However, new technologies enable the view to be presented in a manner which does not resemble the current tower in any way. Views can be presented based on operational need and adapted to suit each environment. This is where additional technology, sensors, data capture techniques, surveillance and visual display solutions can be used. Although not required for the provision of ATS, they can be employed to improve situation awareness and working methods.

The SESAR Operational Services and Environment Description (OSED) (SESAR Joint Undertaking, 2014 (b)) for remote and virtual tower defines the concept as follows:

"Remote tower is where ATS are remotely provided through the use of direct visual capture and visual presentation e.g. through the use of cameras."

The concept is further categorised into three concept applications or modes of operating: Single, Multiple and Contingency, as shown in Figure 1-1 below.

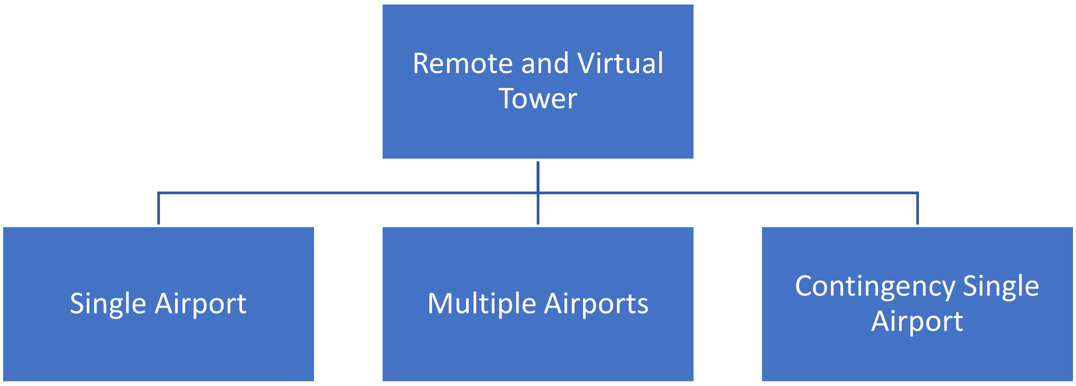


Figure 1-1: Remote Tower concept overview from SESAR

Remote tower project started more than ten years ago as an internal development project between Swedish Air Navigation Service Provider (ANSP) LFV and SAAB in 2006 (the Remotely Operated tower (ROT) project (Furstenau, Norbert, 2016). SAAB also coordinated the EU-Project ART (Advanced Remote Tower-ART) focusing on single remote tower control (Fält & SAAB, 2012) (van Schaik, , F. J.; Roessingh, J. J. M.; Bengtsson, J.; Lindqvist, G.; Falt, K., 2016).

SESAR Remote and Virtual Tower projects (SESAR Joint Undertaking, 2012) followed, aiming to assess the concept's feasibility through several validation activities and determining its contribution to key performance areas. The concept has advanced remarkably fast and the first operational implementation gained approval in April 2015 in Sweden.

While single remote tower and contingency remote tower have been validated and are currently operated, multiple remote tower is not operational, thus a topic of research regarding its feasibility.

1.1 Research Framework and Research Question

In 2016, the Irish Aviation Authority was involved in the development and validation of multiple remote tower operations. The objective of remote operations was to provide Air Movements Control (AMC) and Surface Movement Control (SMC) for Cork and Shannon airports from a remote tower module located in Dublin Air Traffic Control Centre. 50 trials were performed, and the results indicate the potential of the concept and its application in Ireland, while also identifying a list of areas that require improvement (Irish Aviation Authority (IAA) and SESAR Joint Undertaking, 2016). The remote tower system used for the trials is still located in Dublin Airport and the IAA is interested in introducing the multiple remote tower in operation.

Irish Aviation Authority, represented by Desmond Whitty (Unit Safety Manager), in collaboration with supervisor Prof.dr.ir. H.A.P. Blom and student R.E. Tudorica decided to develop an agent-based model for multiple remote tower operations for two airports, using Cork and Shannon airports as examples. The research project is carried out in the Irish Aviation Authority, Dublin, Ireland.

The reason for choosing an agent-based modelling approach is that the model is flexible, the agents can be modified with ease, without being required to change the entire mode. Another important aspect to agent-based modelling is capability of the model to identify emergent behaviour that can be used to propose improvements for multiple remote tower operations.

Research objective

The focus of the MSc. Thesis is to develop an agent-based model for the evaluation of multiple remote tower in Shannon and Cork Airport from one remote tower location in Dublin Airport.

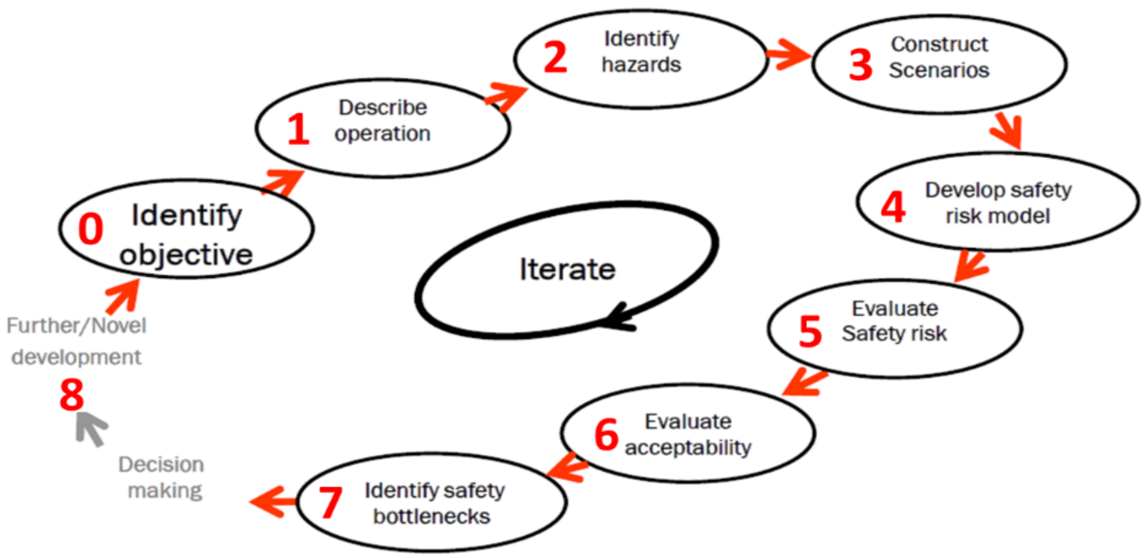


Figure 1-2: Safety Risk Assessment Steps

Figure 1-2 presents the steps of the safety risk assessment as presented in the AE4448 Agent Based Safety Risk Analysis Course (Blom, H.A.P, 2018).

Research framework

This *practice-oriented* research project aims to conduct an agent-based safety risk modelling and simulation of controlling two airports from one remote tower. An overview of the research is presented in Figure 1-3 below.

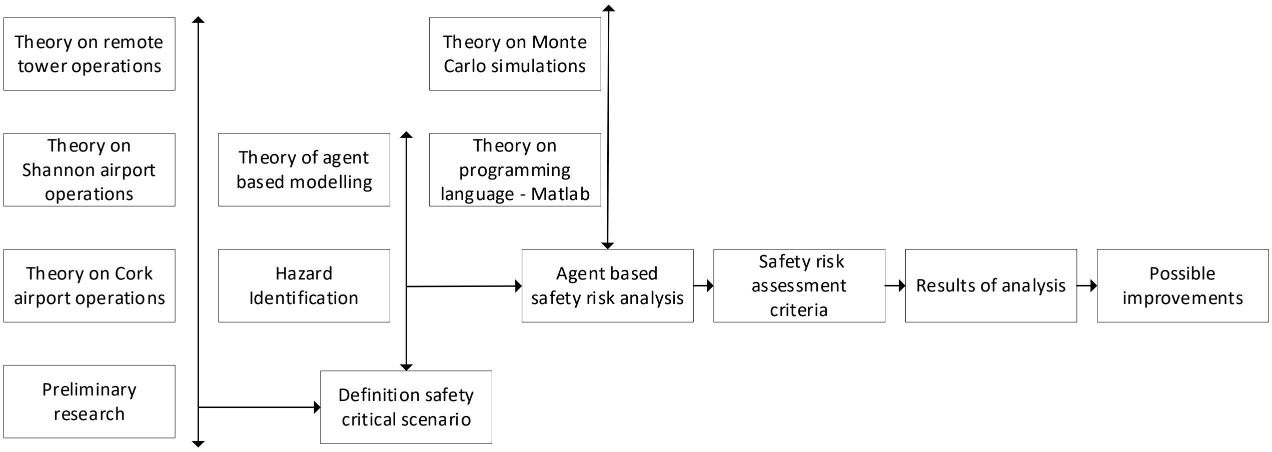


Figure 1-3: Research Framework for the MSc. project

The research framework has been developed using the agent-based modelling process as described in the AE4448 Agent Based Safety Risk Analysis course (Blom, H.A.P, 2018).

Research questions

The MSc. Thesis is intending to answer the three questions below. They have been derived by using the SMART criteria.

1. What is the safety critical operation which is going to be modelled in this research?
2. How can an agent-based model be developed for the most safety critical multiple remote tower hazard?
3. What possible improvements can be proposed from the simulations results?

The focus of the MSc. Thesis is on its use on two airports; following the project outline above and the main research questions, the derived sub-questions to be answered are presented below.

1. What is the safety critical operation which is going to be modelled in this research?
    1.1. What are the characteristics of the system which is going to be modelled?
        1.1.1. What is the definition of remote tower system?

1.1.2. What are the benefits, the current and future application of remote tower operations?

1.1.3. What are the components of a remote tower system?

1.1.4. What are the differences between a “conventional” and a remote tower working environment?

1.2. How is the remote tower system operated?

1.2.1. What are the differences in the air traffic controller working position?

1.2.2. What is the difference between a real on-site tower and a remote tower centre?

1.3. What are the types of remote tower systems available?

1.3.1. What are single remote tower operations?

1.3.2. What are multiple remote tower operations?

1.3.3. What are contingency remote tower operations?

1.4. Which operations are of interest for researchers and stakeholders?

1.4.1. What are the areas in remote tower operations that are open for research?

1.4.2. Which operations are of interest for other researchers?

1.4.3. What operations are of interest for the industry?

2. How can an agent-based model be developed for the most safety critical multiple remote tower hazard?

2.1. What are the hazards associated with multiple remote tower operations?

2.2. What is the hazard most relevant (most safety critical) for modelling?

2.3. Based on question 2.2 what is the operational scenario for the agent-based modelling?

2.4. Which agents are involved in the operation to be modelled?

2.5. How can the actions of the agents be quantified (reaction time, logical decisions, etc.)?

3. What possible improvements can be proposed from the simulations results?

3.1. How will the validation of results be performed by the author (e.g. face-value judgements by subject matter experts)?

3.2. What are the evaluation criteria for the results?

3.3. What is the level of safety associated with the hazard?

3.4. What are the main contributors to the resulting level of safety?

Research Strategy

The research questions presented above are structured in three parts. The first part represents the acquisition of information regarding the remote tower operations, the second part represents the development of the agent-based model, and the third part is the simulation of the model and analysis of the results.

As part of the research strategy, the decision was taken to go for a *depth* view of the research objective. The hazard analysis as per question 2.1. and question 2.2 highlights the relevant hazards associated with multiple remote tower. Furthermore, the most relevant hazard in terms of expected safety impact to the operations are further subjected to an agent-based modelling and analysis. Therefore, a single case study is in scope for the research since it is expected that both the hazard analysis and analysis of the results are time consuming, since it will require gathering expertise from the appropriate subject matter experts.

The first part of the research represents the acquisition of the information through desk research. The purpose of the research is acquiring knowledge and understanding of the remote tower operations, to contribute to the refinement and definition of the scenario for the agent-based model. The materials used for the desk research include both currently available literature and secondary data (airport traffic and safety statistics). The results and outcomes of this research step are recorded in the literature study. Unfortunately, given that this is a novel operation, there is not much research being done, and a lot of it might not be publicly available. Fortunately, the collaboration with the Irish Aviation Authority will result in having access to restricted commercially sensitive data.

As part of the second research question, a hazard identification and analysis is performed, which consists of brainstorming activities with subject matter experts in air traffic operations in both airports, remote towers and safety. The participant list is developed in order to ensure a consistent distribution between the participants and therefore reduce bias. The results of the hazard analysis are recorded. The expected result of the hazard identification and analysis represents a list of hazards and their effect. A hazard is selected for the agent-based modelling and analysis.

Finally, as part of the second and third question of the research, the research strategy chosen is an experiment, in line with the research objective above. This involves a computer experiment, which includes the development of the agent-based model and the MATLAB simulations. No other alternative research strategy is considered, since this experimental set up is a main requirement of this MSc. Thesis.

A final desktop research is be performed to answer question 3.2, aimed at comparing the results of simulation with both the rate of incidents currently present in the two airports, as well as a comparison with the rates of incidents reported internationally. This data available for the author, as being part of the IAA as well as international forums aimed towards sharing aviation incident statistics for safety improvement.

1.2 Organisation of MSc. Thesis

Based on the steps presented in Figure 1-2, the MSc. Thesis is structured as follows:

- **Chapter 1: Introduction** presents the research framework and research questions, and the organisation of the MSc. Thesis.
- **Chapter 2: Literature Study** is the summary of the literature study, the overview of remote tower operations, i.e. single, multiple and contingency tower operations. It also provides an overview of the research gap.
- **Chapter 3: Operation Description** presents an overview of the remote tower concept of operations and of the Shannon and Cork airport operations. This represents Step 1: Describe Operation of the Safety Risk Assessment.
- **Chapter 4: Hazard Identification and Initial Analysis** presents the summary of the hazard identification process for multiple remote tower and initial risk analysis of those hazards. The hazard for the scenario is also selected in this chapter. This represents Step 2: Identify hazards of the Safety Risk Assessment.
- **Chapter 5: Construct Operational Scenario** details the elements of the scenario for the hazard selected in chapter 4. This represents Step 3: Construct Scenarios of the Safety Risk Assessment.
- **Chapter 6: Multi-agent Model of Multiple Remote Tower Operation** provides an overview of the multiple remote tower multi agent model. This represents Step 4: Develop safety risk model of the Safety Risk Assessment.
- **Chapter 7: Simulation Code Development** describes the petri net model, followed by the MATLAB implementation strategy and the presentation of the verification process of the Petri Net model of Multiple Remote Tower.
- **Chapter 8: MC Simulation Results** summarizes the MC scenario being simulated. It also provides an overview of the MC simulation results and comparison with current operations, i.e. do these incidents happen in current operation? This chapter represents Step 5: Evaluate safety risk of the Safety Risk Assessment.
- **Chapter 9: Comparison of MC simulation counts vs. safety criteria** analyses the non-nominal events against safety criteria to determine if the risk associated with these events is acceptable. This represents Step 6: Evaluate Acceptability of the Safety Risk Assessment.
- **Chapter 10: Identification of safety bottlenecks** presents the bottlenecks for multiple remote tower operations. This represents Step 7: Identify safety bottlenecks of the Safety Risk Assessment.
- **Chapter 11: Brainstorming possible improvements for the real operation** provides possible improvement for multiple remote tower operations, by addressing the

bottlenecks identified in the MC simulation. This represents Step 8: Further/Novel Development, the last step of the Safety Risk Assessment.

- **Chapter 12: Conclusion** presents the conclusions of the MSc. Thesis.
- **Chapter 13: References**
- **Appendix A Shannon Airport** presents an overview of Shannon airport layout and detailed traffic analysis.
- **Appendix B Cork Airport** presents an overview of Cork airport layout.
- **Appendix C Notes from the Hazard Identification Human Error Template** details the notes from the hazard identification session.
- **Appendix D List of Hazards from SESAR Safety Assessment** presents a list of hazards and their estimated effects on operations deducted by SESAR JU programme. These have been used as input for the hazard identification sessions.
- **Appendix E SDCPN Specification of Agent- Based Model for Multiple Remote Tower** provides the a SDCPN Model Specification of Agent- Based Model for Multiple Remote Tower.

2. Literature Study

This chapter presents an extract from the literature review and it contains a summary of remote tower concept of operations and the validation activities performed for remote tower to date. Section 2.4 presents the current research gaps for remote tower and introduces the purpose of the MSc. Thesis.

2.1 Remote Tower Concept of Operations

In its essence, Remote Tower is allowing the remote provision of air traffic services to one or more aerodromes from a location that is different than the local aerodrome tower building.

The change that comes with moving the provision of the service to a remote location is that there is no more *"out-of-the-window"* (OTW) view (International Civil Aviation Authority, 2016). Since the air traffic service is meant to remain unchanged, Remote Tower needs to remain compliant with ICAO regulation, that being related to the provision of a *"a continuous watch on all flight operations on and in the vicinity of an aerodrome as well as vehicles and personnel on the manoeuvring area"* (International Civil Aviation Authority, 2016), which *"shall be maintained by visual observation"* (International Civil Aviation Authority, 2016). To allow visual surveillance to continue to be provided without access to an OTW view, the most straightforward solution is employing cameras and screens.

ICAO states that *"In the absence of visual observation of all or part of the manoeuvring area or to supplement visual observation, surface movement radar (SMR) provided in accordance with the provisions of Annex 14, Volume I, or other suitable surveillance equipment, should be utilized to:*

d) monitor the movement of aircraft and vehicles on the manoeuvring area;

e) provide directional information to pilots and vehicle drivers as necessary; and

f) provide advice and assistance for the safe and efficient movement of aircraft and vehicles on the manoeuvring area." (International Civil Aviation Authority , 2001).

This enables the use of surveillance systems such as Surface Movement Guidance and Control Systems (SMGCS) and other Surface Movement Radar (SMR) to be used to substitute the OTW view (International Civil Aviation Authority , 2001).

Remote Tower applications, in operation or in development, are using the following technological solutions:

- Optical Sensors Presentation. The OTW view is obtained using camera technology; and/or

- Surveillance Technologies Presentation. The out-of-the-window view operations are based on procedural control and surveillance technology (e.g. A-SMGCS) (European Organisation for Civil Aviation Equipment(EUROCAE), 2017).

Applying these technologies enables the Remote Tower facility to transform the aerodrome view. At a basic level, Remote Tower facilities may just replicate the traditional tower view. However, the technologies enable the view to be presented in a manner which does not resemble the current tower in any way. Views can be presented based on operational need and adapted to suit each environment. This is where additional technology, sensors, data capture techniques, surveillance and visual display solutions can be used. Although not required for the provision of ATS, they can be employed to improve situational awareness, concept acceptance and working methods.

The SESAR Operational Services and Environment Description (OSED) (SESAR Joint Undertaking, 2014 (b)) for Remote and Virtual Tower defines the concept as follows:

"Remote Tower is where ATS are remotely provided through the use of direct visual capture and visual presentation e.g. through the use of cameras."

The concept is further categorised into three concept applications or modes of operating: Single, Multiple and Contingency, as shown in Figure 2-1 below.

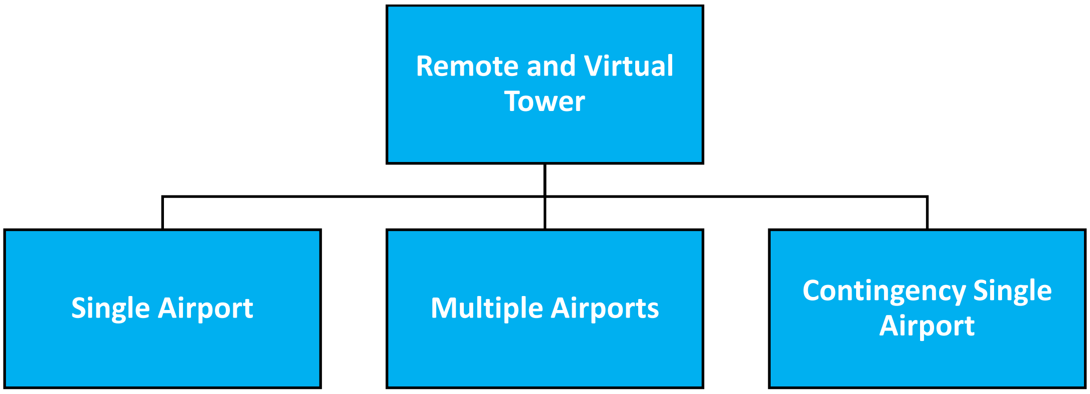


Figure 2-1: Remote Tower concept overview from SESAR

Based on the definitions above, the remote tower concept and the technological solutions that are operational today are summarized below, in Table 2-1.

Table 2-1: Remote Tower Concepts Overview

	Optical Sensors Presentation *(e.g. cameras)*	**Surveillance Technologies Presentation *(e.g. A-SMGCS)***	**Optical Sensors Presentation + Surveillance Technologies Presentation *(e.g. A-SMGCS)***
Contingency Single Airport	x	√	x
Single Airport	√	x	√
Multiple Airports	x	x	X

Single Remote Tower Operations

From SESAR's definition (SESAR Joint Undertaking, 2014 (b)), Single Airport Remote Tower is defined as: *"…The objective of Remote Provision for a Single Aerodrome is to provide the ATS …for one aerodrome from a remote location i.e. not from a Control Tower local to the aerodrome. "*

Single Remote Tower, in the incipient phase, is intended to be applied as a solution for most of the small aerodromes, where the airspace complexity is also low, and mostly single simultaneous operations.

Implementing single remote tower can be beneficial in multiple scenarios, such as:

- **Isolated or dangerous areas,** since it might be difficult persuading ATCO/AFISOs to move to very remote locations, or it can also be too dangerous to operate a local facility (typically areas of high military activity);
- **Temporary locations,** in cases where local tower must be closed for an extended period, such as maintenance or re-building of the tower.
- **Merge of TWR and Approach (APP) control,** by integrating them into a Remote Tower with the TWR controller even able to share the APP control tasks, depending on traffic levels and ATCO rating. Some airports have already merged TWR and APP, so the transition to a combined remote solution can be more straight-forward.
- **Flexibility of access,** due to the ability to use staff in a more flexible manner. This allows for the extended aerodrome/airspace opening hours and as such improves the airspace user's access to the airspace.
- **Replacing a local tower,** cases where a new aerodrome tower needs to be built, or an old one replaced.
- **"Switch mode",** where a single ATCO/AFISO to provide ATS to more than one aerodrome in sequence and providing cost efficiencies.

Multiple Remote Tower Operations

SESAR (SESAR Joint Undertaking, 2014 (b)) defines Multiple Remote Tower by: *"The objective of Remote Tower control for multiple aerodromes is to provide the ATS ….for more than one aerodrome, by a single ATCO/AFISO and implemented from a remote location i.e. not from individual control towers local to the individual aerodromes. The full range of ATS should be offered in such a way that the airspace users are not negatively impacted (and possibly benefit) compared to local provision of ATS."*

The main intended use case for Multiple Remote Tower applications are, in terms of size, the very small aerodromes, with very low traffic numbers. Like Single Remote Tower, Multiple Remote Tower can be used for anything from an isolated area to replacing a traditional tower, and even having to close the aerodromes due to financial difficulties.

Multiple Remote Tower is where maximum cost efficiencies are expected, by centralisation of staff and facilities. This will result in a significant decrease in the facilities and staff required to control the same number of aircraft, in other words, significant savings.

Nonetheless, under SESAR's research, stepwise approach has been preferred, and so far, Multiple Remote Tower only refers to one air traffic controller offering ATS to two aerodromes. Unfortunately, this implies to some extend that the use cases are very limited, oriented like in the case of Single Remote Tower towards very small aerodromes with a very low number of movements.

Contingency Single Airport Operations

Under ICAO (International Civil Aviation Authority, 2016) (International Civil Aviation Authority, 1984), it is a state's responsibility to provide air traffic services to the airspace under its control. Additionally, in case of disruptions, the state shall take appropriate measures to ensure the safety of operations, and if possible, to ensure the continuity of service. For that purpose, states are required to produce appropriate contingency plans.

SESAR (SESAR Joint Undertaking, 2014 (b)) defines Contingency Remote Tower as*:" The objective of ATS during contingency events is to provide the ATS… for one aerodrome from a remote location i.e. not from a Control Tower local to the aerodrome.."*

Contingency applications, as presented above, can have a planned nature such as planned maintenance or planned expansion/upgrade of the traditional airport tower which might require a relocation of ATS. It can also be used in the case of unplanned events which might develop into emergency situations. Not providing a service for a given time might turn out to have disastrous effects on the ATM network since the airport would need to be closed.

Therefore, having the possibility to continue the provision of ATS, even though maybe not at a full capacity could bring many benefits.

The target environments for Contingency Remote Tower are airports with medium to high traffic, since in case of low-density aerodromes is, most of the times, not very problematic to divert the traffic to neighbouring aerodromes, or closing the airport might not have grave consequences over the ATM network (Jankovec, 2014).

SESAR, following a stepwise approach, has started looking at contingency solution for medium size aerodromes, with the intent to extend the use in the future to high density airports, and even provide such a thing as 100 % capacity in contingency situations.

2.2 Real Time Simulations IAA Multiple Remote Tower (Large Scale Demonstration)

Multiple Remote Tower operations have been introduced in Ireland, on a trial basis, to support the operations in Shannon and Cork airports during periods of low traffic density.

This solution was based on the SESAR remote tower concepts for a single airport and multiple airports.

The remote tower module was comprised of an "out-of-the-window" (OTW) view (cameras), with information provided by the electronic flight strips (EFS) and the radio communication network.

The multiple remote tower operations involved one air traffic controller handing the traffic for the two airports simultaneously. Nonetheless, when it came to the validation exercises, the focus was split into simultaneous and in sequence traffic.

In sequence was defined as: *"Where the spacing between two aircraft arriving or departing at Cork and Shannon airports is equal to or more than the spacing which would be required if the two aircraft were landing or departing at the same airport. "* (Irish Aviation Authority, 2016)

Simultaneous movements were defined as: *"Where the spacing between two aircraft arriving or departing at Cork and Shannon airports is less than the spacing which would be required if the two aircraft were landing or departing at the same airport."* (Irish Aviation Authority, 2016)

The IAA Multiple Remote Tower Large Scale Demonstration results included the following recommendations for the CONOPS:

- **Simultaneous arrivals:** *"When in a Multiple Airport Simultaneous Operations (MASO) environment and with two simultaneous arrivals into two different airports ideally the first landing aircraft should be steady on the Runway before the second arrival aircraft is 1NM from touchdown at the other aerodrome. Meeting this guideline has been identified as difficult and it could happen that this guideline could not be accomplished due to varying speeds on final approach of the two aircraft. Any such recommendation when implemented in the future would be supported by an additional caveat such which should give the Controller the authority to exercise professional judgement with regard to the issuance of a landing clearance to the arriving aircraft: In this regard Controller will use a number of factors in deciding if second aircraft can to continue to land, such as:*
    - *Is the arrival Runway clear of obstructions;*
    - *Prevailing weather;*
    - *Complexity of the workload."* (Irish Aviation Authority, 2016)
- **Simultaneous Departure:** *"In a Multiple Airport Simultaneous Operations (MASO) environment with two simultaneous arrivals into two different airports, some spacing should exist between them, perhaps around 2NM between the landing aircraft and the aircraft on approach at the second airport. However, due to the unpredictability of speeds at the final stages of approach this is not a conclusion and was further explored in subsequent exercises.*

- **One departure at one airport followed by an arrival at the other airport:**" *In a Multiple Airport Simultaneous Operations (MASO) environment with one departure at one airport followed by an arrival at the other airport, ideally time should be allowed after the cleared for take-off instruction so that the Controller can monitor the roll and initial rotation of the departing aircraft before the arrival aircraft is 1NM from touchdown at the other aerodrome."* (Irish Aviation Authority, 2016)

- **One departure at one airport followed by an arrival:** *"In a Multiple Airport Simultaneous Operations (MASO) environment with one departure at one airport followed by an arrival at the other airport, ideally time should be allowed after the cleared for take-off instruction so that the Controller can monitor the roll and initial rotation of the departing aircraft before the arrival aircraft is 2NM from touchdown at the other aerodrome."* (Irish Aviation Authority, 2016)

- **Training traffic performing a simulated engine failure at one airport:** *" In a Multiple Airport Simultaneous Operations (MASO) environment and with training traffic performing a simulated engine failure at one airport, it is recommended that a clearance for take-off to an aircraft in the other airport would not be given until the aircraft performing the simulated engine failure reported that the aircraft had recovered from the simulated engine failure, or that the request for a simulated engine failure after take-off would be deferred until there was no critical phase movement at the other airport."* (Irish Aviation Authority, 2016)

While a success, the multiple remote tower trial has demonstrated that consideration must be given to this operation. In particular, the results have indicated the following differences compared to local single airport operations:

- The results have indicated that capacity might be negatively affected in the cases where Low Visibility procedures were in place (visual representation was not as good as the local tower). Also, unexpected VFR traffic has to be accommodated which results in an increase perceived workload and a negative impact on capacity (aircraft delayed arrival).

- While it was recognised that the remote tower module is state of the art, there were instances where system capabilities required improvements, in terms of the design, use and operation.

2.3 Safety Assessment SESAR Joint Undertaking of Single Remote Tower

Under the aegis of SESAR, the concept has developed from just a proposal stage to real implementation in 2015. The Remote Tower work has been developed in two projects, i.e. Project 06.09.03 Remote and Virtual Tower (SESAR Joint Undertaking, 2014 (a)) and Project 06.08.04 Coupled AMAN-DMAN (SESAR Joint Undertaking, 2011) (Friedrich & Möhlenbrink) focused on single, multiple and contingency uses. As part of the projects, many ANSPs have supported the validation process.

SESAR represents a European Union initiative meant to completely overhaul European airspace and its air traffic, by setting ambitious goals as enabling the EU airspace to handle three times more traffic, improve safety by a factor of 10, and reduce environmental impact, while in the same time reducing the ATM cost to half.

Within SESAR, two research projects are tasked with developing and validating the Remote Tower concept system and/or advanced technologies in order to be able to provide remotely operated ATS to airports. In SESAR the concept is referred to as Remote and Virtual Tower. The SESAR projects include P06.09.03, which involves NORACON and NATMIG and P06.08.04 involving DLR and DFS.

The SESAR Operational Services and Environment Description (OSED) for Remote and Virtual Tower defines the concept as follows:

"Remote Tower is where ATS are remotely provided through the use of direct visual capture and visual presentation e.g. through the use of cameras." (SESAR Joint Undertaking, 2014 (b))

In terms of potential applications of these three sub-categories of Remote Tower, SESAR has started by looking at the following environments:

- Remote Provision of ATS (TWR & AFIS) to a Small to Medium Single Aerodrome (SDM-0201);
- Remotely Provided Air Traffic Services (TWR & AFIS) for two low density Aerodromes (SDM-0205);
- Remotely Provided Air Traffic Service (TWR) for Contingency Situations at Small to Medium Aerodromes (with a Single Main Runway) (SDM-0204).

The first two applications are presented as a solution for small aerodromes with low traffic as a replacement of the local tower, whereas the contingency solution is directed towards medium to high density aerodromes to serve as a contingency solution.

Although these definitions seem very comprehensive, it might be that in the end they have a constraining effect over the Remote Tower use cases. For instance, Single Remote Tower is limited to low traffic aerodromes, while Contingency Remote Tower is mostly targeted for medium and high-density aerodromes.

These definitions come from the current European ATM research (SESAR Joint Undertaking, 2014 (b)), where SESAR has imposed a series of constraints to possible applications. This was done so ease the research, by taking a staged approach to validating the concept. However, these are not the definitions of the "wider concepts" of either single, multiple or contingency. SESAR recognises that these applications have wider applications than what has been assessed to date.

2.4 Research gap

Remote tower represents a solution in a multitude of use cases, from low density low business margin airports, to large airports undergoing expansion. For most use cases, the primary driver for implementing Remote tower is cost effectiveness, with other benefits stemming from improved resilience, availability and flexibility of ATS provision.

Table 2-2: Remote tower Concept Status Overview

	Single remote tower	Contingency single remote tower	Multiple remote tower
Safety Assessment	√	√	√
Other Validation *(e.g. live trials, real time simulations etc.)*	√	Trials performed, but concept is not operational	√
In Operation	Validated and operational since 2015	x	Validated and operational in London Heathrow and Budapest Airport

Table *2-2* represents a high-level summary of the current status of Remote tower operations in the world. While single remote tower operations and contingency remote tower operations (based on the principles of the single remote tower operations) have been validated and are currently operated, the multiple remote tower Concept is not operational, and there are not many projects looking at its feasibility.

In order to prove its operational feasibility, SESAR (SESAR Joint Undertaking, 2016 (a)) has started validating the concept via a stepwise approach, from single remote tower operations in a small aerodrome with low traffic. Next, the research has been focused on validating the concept, which is expected to add the most cost efficiency, i.e. multiple remote tower.

The current research is focusing on analysing the multiple tower operation, following a human centred approach when looking at improving the technological solutions and assessing workload. All research use assumptions about the limitation of the traffic, which are deducted from subject matter expertise. Nonetheless, while very valuable, the results of the research are not based on a quantitative assessment.

Moreover, most of the research is centred into the limitations of the ATCO, there is no focus on the other stakeholders (e.g. pilots, airports), or any emergent behaviour stemming from adding all the operations into a multiple remote air traffic control environment.

Currently, there is no available model looking into multiple remote tower model.

Therefore, developing an agent-based model, could provide additional insight into the feasibility of this new concept of air traffic operations, by considering all actors and not only the ATCO, and moreover could be utilised in safety cases to assess the safety level of multiple remote tower operations

Table 2-3 below represents a summary of the ongoing projects looking into the multiple remote tower, i.e. existing work, methods used, and the conclusions of the studies.

Table 2-3: Summary of ongoing multiple tower projects

Reference	Project name and initiators	Project objective	Methods or modelling techniques	Results and limitations
(Irish Aviation Authority, 2016)	**Irish Aviation Authority LSD 02.04**	Demonstration exercises focused on human performance, safety, capacity and cost efficiency, in order to provide proof of concept for remote tower services provision for multiple airports	Fifty live trial exercises (Air Movements Control and Surface Movements Control) for Cork and Shannon airports provided from the remote tower Centre in Dublin Airport. Assessment methods: live exercises and debriefings.	*"The live trial exercises demonstrated that the ATS provided by the RTC for a single airport and two medium airports by a single Controller with 'in sequence' and 'simultaneous' aircraft operation was at least as safe as the ATS provided by the Local towers at Cork and Shannon aerodromes."* (Irish Aviation Authority, 2016)
(Kearney, Li, Braithwaite, & Greaves, 2017) **(Li, 2016)**	**Irish Aviation Authority**	Evaluation of Human Performance for multiple remote tower operations	Hierarchical Task Analysis for multiple remote tower operations, Human Error Template, NASA-TLX, Eye Tracker	The results have indicated that the technological solution can support the implementation of the concept, yet the high increase in workload must be further analysed before local final implementation.

(Svensson & Forsell, 2017)	**Linköping University**	Analysis of work patterns for human-automation communication in multiple remote towers	Eye-tracking measurement in a multiple remote tower Simulator (with 3 airports)	The results have indicated the influence of the technological solutions on the level of provision of multiple remote tower service. The potential to have more airports than three, as in this study, or more complex or intense traffic, depends on the quality of human-automation collaboration.
(Josefsson, Polishchuk, & Polishchuk, 2017)	**LFV Research & Innovation Communications and Transport Systems, Linköping University**	Optimal assignments of the airports to the remote tower Modules (RTM)	Mathematical model using integer programming. As input one-day airport data schedules is used as well as assumption and constraints related to the operations, such as maximum number of airports per RTM (2), maximum movements (per hour 10, per 5 minutes to 3)	The results indicated the influence of the expected traffic on the configuration of the remote tower Centre. Nonetheless, the assumptions and constraints are based on subject matter expertise and there is no indication what is the maximum number of aircraft that can be handled in a particular traffic scenario. More research looking into these assumptions is needed.

(Moehlenbrink, Christoph; Papenfuß, Anne ; Jakobi, Jörn, 2011)	**German Aerospace Centre (DLR)**	Role of Workload in a remote tower Centre	Questionnaires: For observers: Cooper-Harper-Scale based questionnaire was developed to evaluate remote tower centre aspects from an operational perspective. For controllers: Instantaneous Self-Assessment (ISA)scale workload data were collected. After each simulation run, the controllers filled out the NASA-TLX.	The results highlighted the importance of workload definition and assessment, especially for this novel operation. As part of the results, the safety critical situations in a multiple environment were identified as being callsign similarity and simultaneous requests from two aircraft, which are also expected in a single airport ATC. Moreover, the results indicate that during smooth operations, parallel starts of aircraft, or even parallel landings were rated as uncritical events.

(Herrera, Ivonne; Smoker, Anthony ; Pinska-Chauvin, Ella ; Feuerberg, Beatrice; Schwarz, Michaela ; Laursen, Tom; Josefsson, Billy)	**SINTEF, IFATCA, Lund University NAVIAIR, EUROCONTROL, NORACON**	Resilience Engineering (Re) In Design: Initial Application of a new reassessment method to the multiple remote tower concept	Initial application of a resilience engineering (RE) assessment method to the multiple remote towers (MRTWR) concept.	The key results of the assessments included highlighting a new set of interfaces and interdependencies in the day to day operations as well as the need to analysing different scanning patterns and workload prioritisation.

3. Operations Description

This chapter provides an overview of the concept of operations for multiple remote tower, as well as the airports considered in the MSc. Thesis, i.e. Shannon and Cork. This represents Step 1 of Figure 1-2.

Shannon Airport was established in 1942 and was the first airport in the world to welcome transatlantic flights.

Based on (Irish Aviation Authority, 2019), Shannon is a single runway, non-complex surface layout. In terms of operations, there is a mix of VFR, regional and transatlantic flights that are operating in Shannon, with less than 30,000 movements per year.

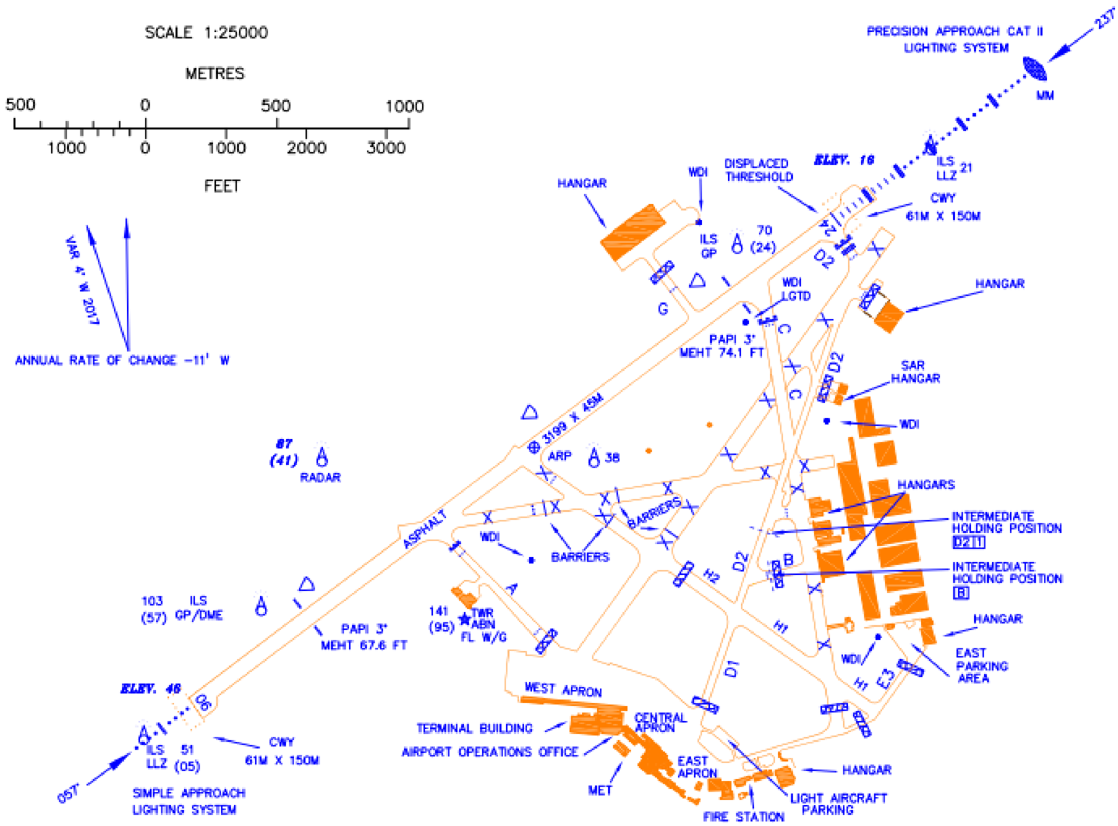


Figure 3-1: Shannon Airport Layout (Irish Aviation Authority, 2019)

Cork Airport was established in 16 October 1961. It is the country's second largest and best-connected international airport with more choice of routes than any other airport outside of Dublin.

As presented in Appendix B Airport Layout Cork is a dual runway, with non-complex surface layout. In terms of operations, there is a mix of VFR, regional and transatlantic flights that are operating in Cork, with more than 50,000 movements per year.

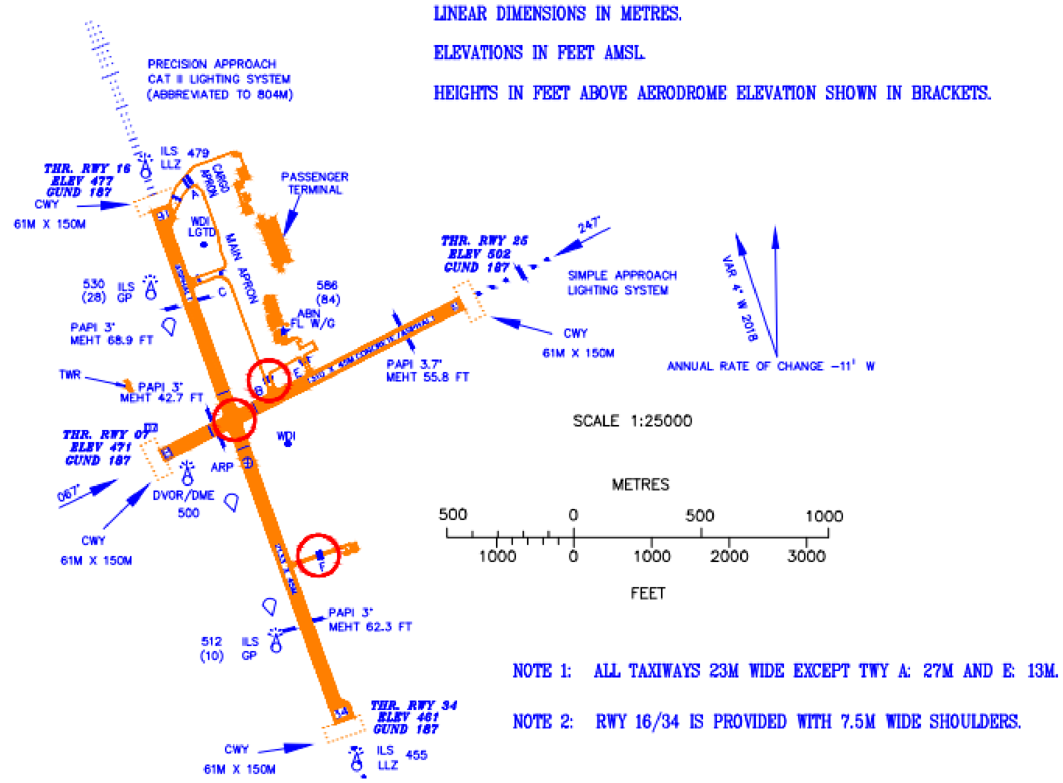


Figure 3-2: Cork Airport Layout (Irish Aviation Authority, 2016)

These two airports are used as the basis for the case study for the MSc. Thesis, as multiple remote tower is already planned to be implemented at these airports.

3.1 Concept of Operations for Multiple Remote Tower at Shannon and Cork Airport

As presented in Chapter 2, SESAR (SESAR Joint Undertaking, 2014 (b)) defines Multiple Remote Tower by: *"The objective of Remote Tower control for multiple aerodromes is to provide the ATS ….for more than one aerodrome, by a single ATCO/AFISO and implemented from a remote location i.e. not from individual control towers local to the individual aerodromes. The full range of ATS should be offered in such a way that the airspace users are not negatively impacted (and possibly benefit) compared to local provision of ATS."*

The Shannon cameras are located between the existing ATC Tower and the Runway and are at a height of 20.615m. The viewing angle is similar to the local Shannon Tower, but it is not as high as the local tower. The Cork cameras are located behind the existing ATC Tower slightly further away from the runway than the local Tower. The Camera height is 26.615m and provides for the same viewing aspect as the local Tower. The height of the camera mast exceeds that of the local Cork Tower (Irish Aviation Authority, 2016).

Figure 3-3: Cork Remote Tower Camera (Irish Aviation Authority, 2016)

The Remote Tower Centre is equipped with two opposite facing Remote Tower Modules comprising of 15 screens in each (14 active and one spare). Each of the modules is equipped with EFS and radar data display which is used only as a distance to touchdown indicator and not to provide a radar service (Irish Aviation Authority, 2016). Each of the modules accommodates two Controller positions i.e. SMC and AMC.

For the scenario, ATCO will perform both tasks, i.e. SMC and AMC. The procedures that the ATCO will use in managing both airports at the same time were developed and used as input for the hazard identification and risk analysis step. The procedures are detailed in Appendix C.

Figure 3-4: IAA Remote Tower Module (Irish Aviation Authority, 2016)

3.2 Shannon Airport Operations Analysis

Yearly Traffic Distribution

Based on the 5 years historical data, the traffic in Shannon Airport has not changes much, with total traffic remaining between 23,000 to 25,000 movements/year. The traffic in 2018 is only available until August, yet it is clear that it follows the trend of the previous years.

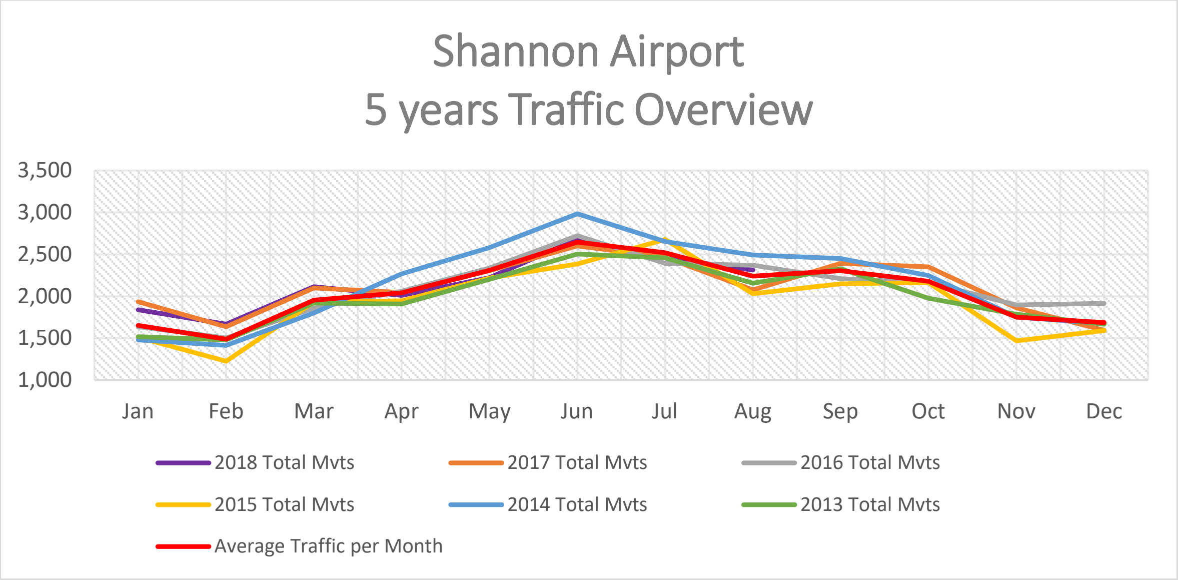


Figure 3-5: Shannon Airport 5 years traffic overview and associated monthly average traffic

Airport Departure Distribution

Number of flights/day/months

Given the distribution of the flights per hour presented above and the big differences per hour and per month encountered, further data was requested on the daily distribution of the flights. The latest one-year data available was used, i.e. 2017.

Figure 3-6 shows that there is a very large variation between the summer and winter season for Shannon airport. While in the winter the number of departures is around 20 per day, the summer has experienced almost 50 departures/day.

Month	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
01	16	26	20	26	28	29	19	24	25	28	24	22	28	22	29	29	33	30	28	34	19	24	28	21	24	25	26	23	30	30	26
02	19	23	31	26	22	28	25	22	29	29	19	25	26	23	23	18	28	21	26	27	17	29	24	25	19	29	31	23			
03	20	26	31	17	33	25	22	23	25	24	18	27	43	17	26	32	27	30	30	37	29	21	32	33	24	29	28	26	25	34	34
04	28	23	30	29	26	33	37	24	27	29	24	30	28	31	20	27	26	23	28	32	30	20	30	30	21	26	33	32	21	24	
05	27	23	34	30	33	29	32	35	28	26	30	35	25	31	34	25	34	32	38	30	33	33	29	28	35	38	27	29	41	31	26
06	37	33	30	30	29	29	25	41	39	31	30	37	31	36	41	45	30	35	40	34	40	48	49	33	36	42	39	32	38	38	
07	26	36	35	33	32	38	36	33	34	37	29	34	34	33	39	34	41	29	29	35	40	24	33	36	28	27	34	39	34	38	34
08	30	38	37	29	34	38	31	30	28	30	33	33	34	36	28	30	28	36	27	30	35	32	29	32	36	23	30	33	27	24	32
09	36	28	29	39	25	26	26	32	25	33	36	31	28	34	39	27	39	31	34	32	37	32	25	34	39	28	28	34	39	25	
10	40	38	30	30	29	32	31	33	32	28	28	33	35	30	40	17	40	32	34	36	29	32	40	30	39	37	33	31	27	37	30
11	23	26	28	35	32	26	26	32	28	27	30	27	31	29	24	29	28	23	27	30	26	22	23	25	21	28	24	20	23	25	
12	24	21	27	30	18	28	28	34	28	23	29	24	22	23	38	24	21	25	25	29	31	30	20	16	3	15	24	22	21	21	13

Figure 3-6: Shannon Airport Number of Departures per day (Jan 2017 to Dec 2017)

Time Distribution per month/year[1]

Figure 3-7 shows that the differences in traffic per hour and traffic per month are very high and very season and time of the day dependent.

In terms of traffic hourly distribution, based on the data available, it can be observed that prior to 7 am the traffic is very low, with max 1 flight per hour. After 7 the flight is slowly building up, with traffic reaching up 6 flights/hour in the 12:00-12:59 time interval. The number of flights is dropping after 14:00, with another small peak encountered after 17:00(4 flights/hour).

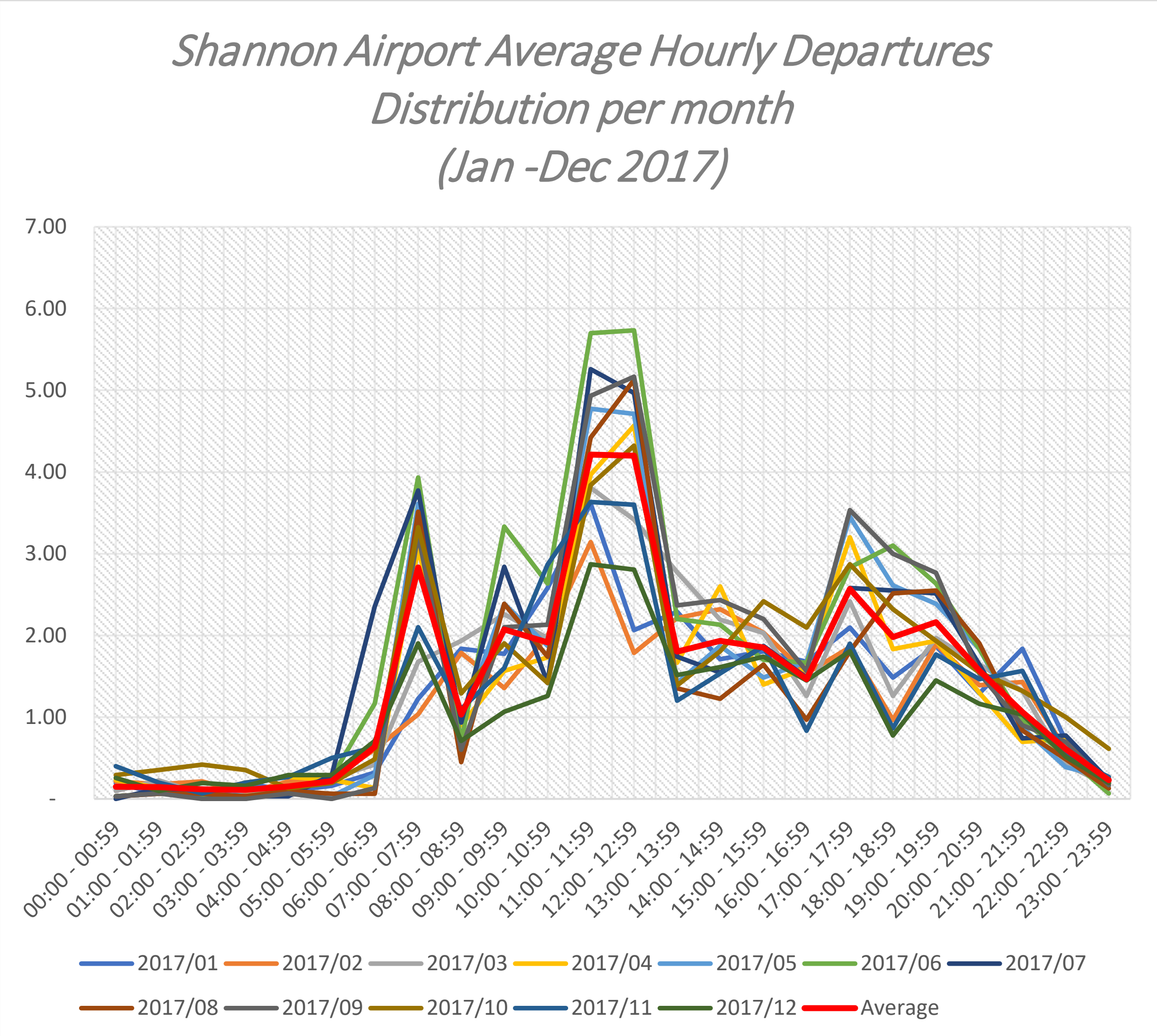


Figure 3-7: Shannon Airport average hourly Departure Distribution per month (Jan-Dec 2017)

[1] The traffic/hour/day is detailed in Appendix A

Airport Arrivals Distribution

Number of flights/day/months

Given the distribution of the flights per hour presented above and the big differences per hour and per month encountered, further data was requested on the daily distribution of the flights. The latest one-year data available was used, i.e. 2017.

As it can be seen in Figure 3-8, here is a very big variation between the summer and winter season for Shannon airport. While in the winter the number of arrivals is around 20 per day, the summer has experienced almost 50 arrivals/day.

Month	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
01	15	27	25	25	28	25	26	22	30	28	18	26	28	28	27	37	26	23	33	32	20	21	29	25	18	25	24	26	30	27	30
02	17	26	30	23	23	28	23	22	28	31	18	26	25	25	22	18	30	21	23	27	21	22	27	24	20	33	29	23			
03	21	29	26	23	27	22	24	24	24	26	19	28	40	22	29	30	25	29	25	38	27	25	31	33	21	30	29	29	23	35	38
04	24	23	30	33	26	35	39	23	27	28	25	23	27	32	18	27	27	29	24	32	34	22	34	28	24	22	29	31	20	27	
05	25	29	29	31	35	29	28	34	30	30	33	37	25	30	37	28	28	36	38	33	31	35	28	26	38	36	25	30	39	31	25
06	36	37	33	30	25	26	28	40	38	30	29	37	38	32	41	42	33	35	38	37	41	47	44	36	36	46	33	33	37	43	
07	28	33	34	26	28	37	39	32	36	37	29	31	37	37	33	36	40	29	27	36	42	29	31	33	31	24	35	37	35	37	38
08	31	38	34	33	35	35	33	30	28	33	34	34	31	39	27	31	27	37	27	29	38	30	31	29	36	25	30	32	27	25	32
09	37	29	29	35	28	24	27	35	27	29	36	32	27	35	40	29	40	36	33	36	35	35	24	31	39	28	30	36	41	28	
10	41	36	30	30	28	42	29	32	30	34	27	34	39	29	38	20	35	27	34	41	34	29	39	34	36	40	37	30	33	33	31
11	26	26	34	29	30	30	31	32	25	33	27	26	35	23	21	27	32	23	29	26	28	19	23	24	19	29	23	21	28	21	
12	30	19	24	31	21	28	24	39	24	25	25	22	23	30	30	22	23	23	25	28	27	26	23	17	2	12	23	24	22	21	16

Figure 3-8: Shannon Airport Number of Arrivals per day (Jan 2017 to Dec 2017)

Time Distribution per month/year

Given the large amount of scattered data, monthly values were used and not daily.

Figure 3-9 shows that, like for departures, the differences in traffic per hour and traffic per month are very high and very season and time of the day dependent.

In terms of traffic hourly distribution, based on the data available, it can be observed that prior to 6 am the traffic is very low, with max 1 flight per day. In between 06:00 and 06:59 the arrivals are peaking up to more than 6 arrivals/hour. Another arrival peak is between 10:00 and 10:59 with ± 4 arrivals/hour. The arrivals are slowly decreasing throughout the day, with ± 2 arrivals/hour 17:00.

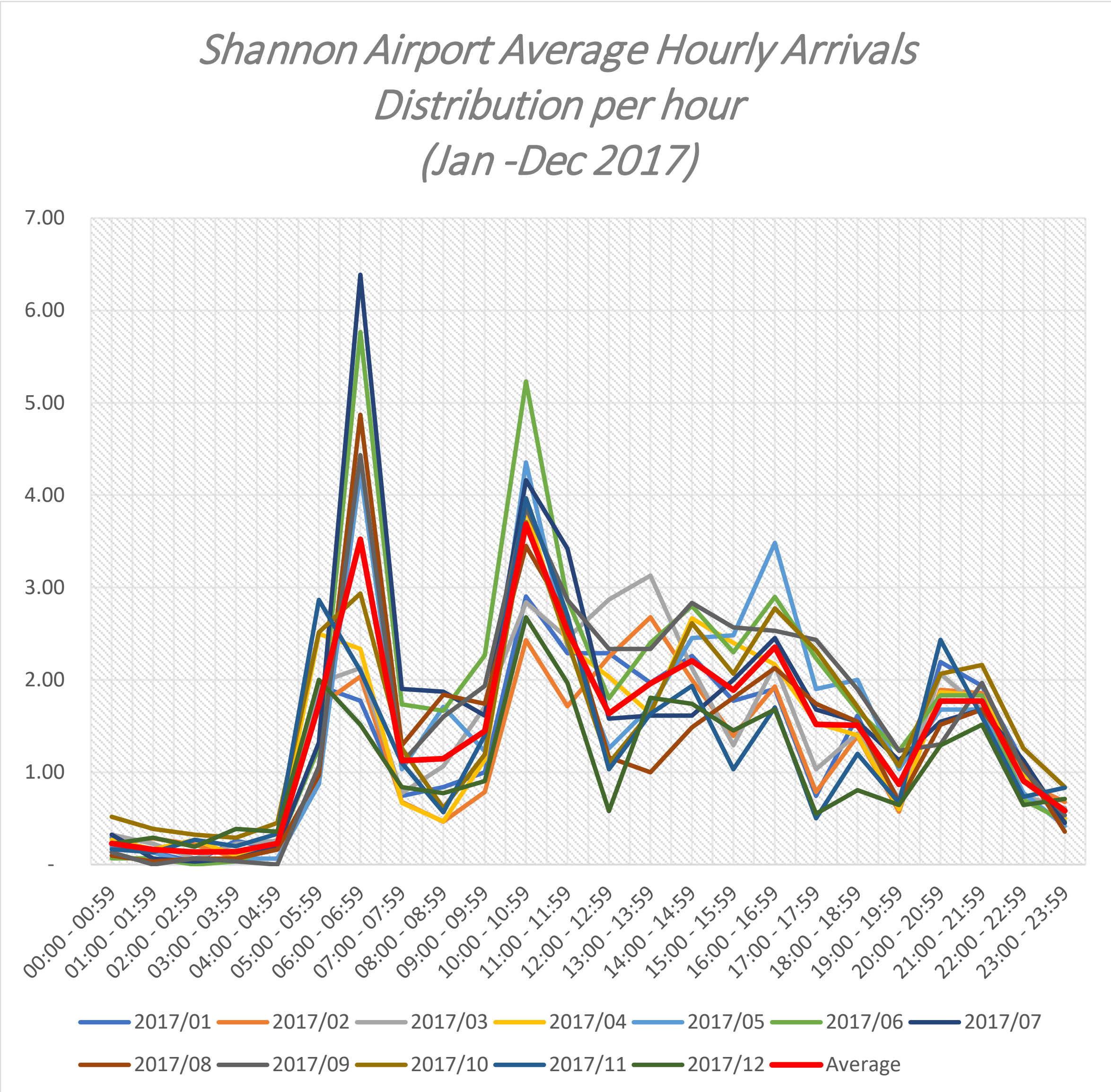


Figure 3-9: Shannon Airport Hourly Arrival Distribution per month (Jan-Dec 2017

Type of traffic

ICAO PANS-ATM-Doc 4444 Air Traffic Management (International Civil Aviation Authority, 2016) defines wake turbulence categories of aircraft as light, medium and heavy. Based on that definition, Shannon airport had in 2017 27% light aircraft traffic, 66% medium aircraft and 7% heavy aircraft.

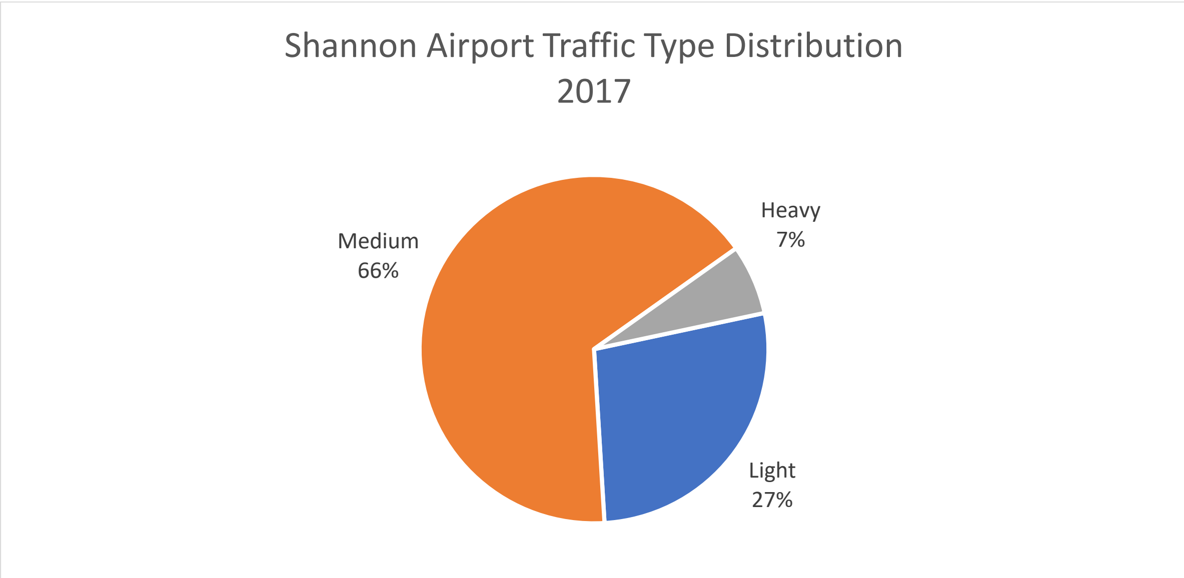


Figure 3-10: Shannon Airport distribution of traffic type as per ICAO Doc 4444- light/medium/heavy (Jan 2017 to Dec 2017)

Ground operations

Appendix A presents the airport diagram, the runway and associated taxiway system. Using SME, it was estimated that the taxiways can be used in the same time with independent departures and arrivals, i.e. an aircraft landing can just vacate the runway without being in a conflict with another aircraft on the taxiway.

Number of gates available: t presents ground airport diagram, including the terminal and gates layout. Using SME input, it was estimated that given the gates layout structure the airport cannot accommodate more than 15 aircraft at any given time.

Runway Analysis

Shannon Airport has a single runway, 06/24, with the main runway in use being Runway 24, with more than 80% of traffic on Runway 24.

3.3 Cork Airport Operations Overview

Monthly Traffic Distribution

Based on the 5 years historical data, the traffic in Cork Airport has not changes much, with total traffic remaining between 40-50,000 movements/year, with record traffic of more than 50,000 movements/year in 2016. The traffic in 2018 is only available until August, yet it is clear that it follows the trend of the previous years.

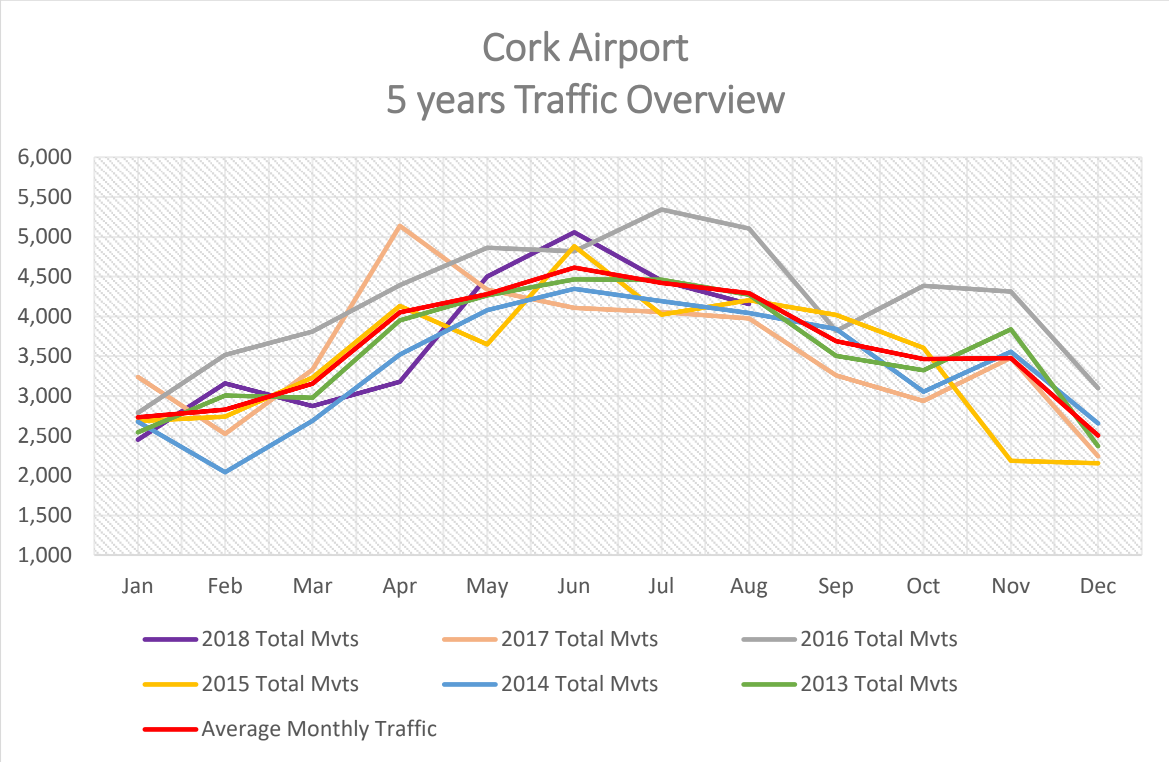


Figure 3-11: Cork Airport 5 years traffic overview and associated monthly average traffic

Airport Departure Distribution

Time Distribution per month/year[2]

Figure 3-12 presents the differences in traffic per hour and traffic per month. The differences are very high and very season and time of the day dependent.

In terms of traffic hourly distribution, based on the data available, it can be observed that prior to 3 am the traffic is very low, with max 1 flight per hour. After 7 the flight is slowly building up, with traffic reaching up 6 flights/hour in the 5:00-5:59 time interval. The number of flights is dropping after 14:00 to not more than 3 flights/hour.

[2] The traffic/hour/day is detailed in Appendix B

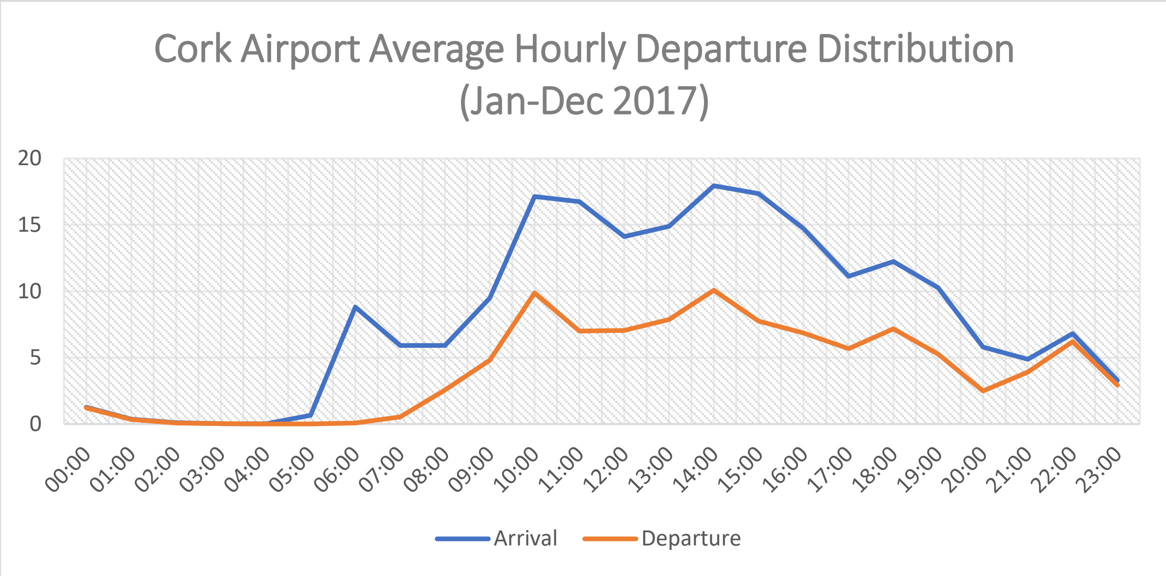


Figure 3-12: Cork Airport Average Hourly Departure Distribution (Jan-Dec 2017)

Traffic Type Analysis

Figure 3-13 presents the distribution of traffic in Cork, i.e. commercial vs non-commercial flights, i.e. 54% flight are non-commercial while 46% are commercial.

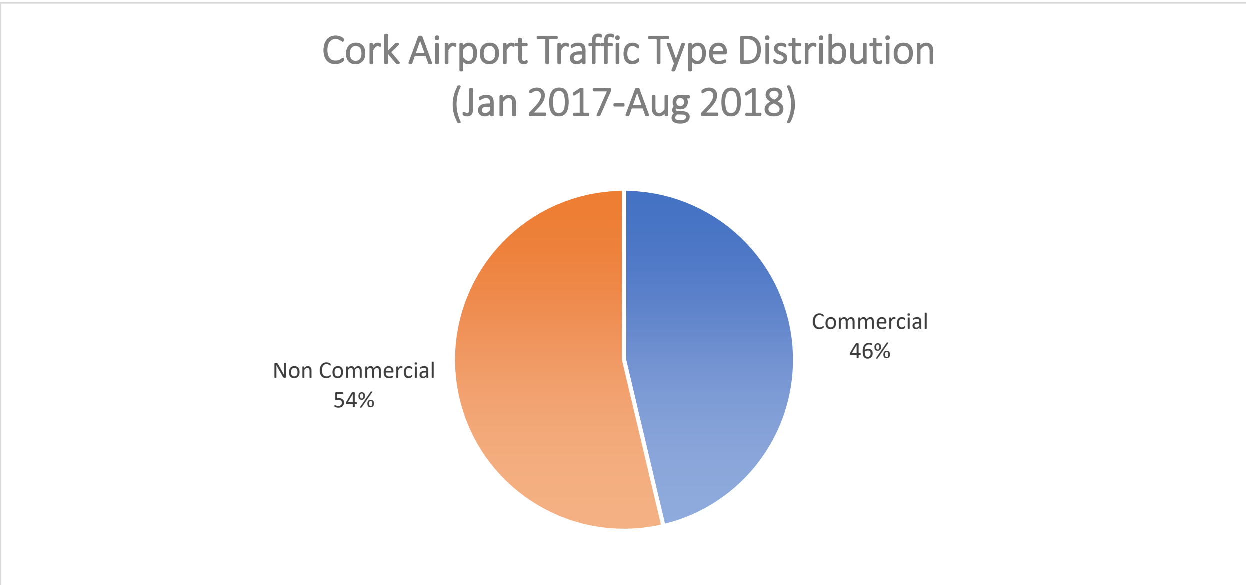


Figure 3-13: Cork Airport Traffic Type Distribution (Jan 2017-Aug 2018)

In terms of commercial flights, most flights are scheduled traffic, totalling 97.95% with less than 1% charter, positioning and diversion flights.

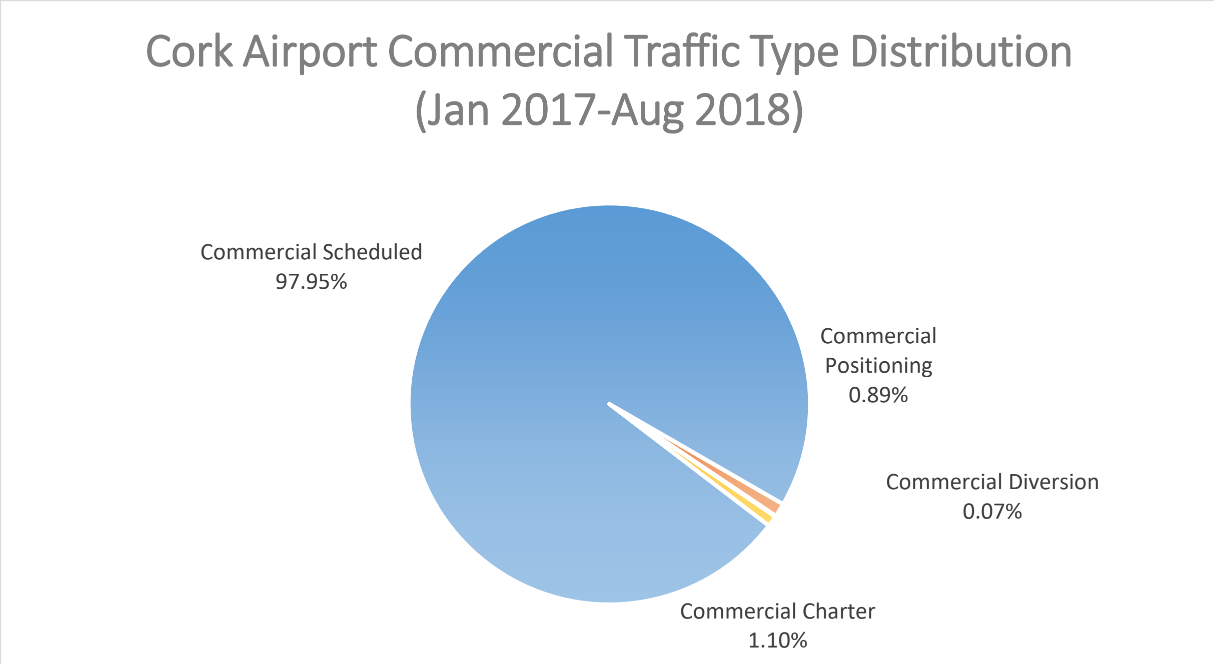


Figure 3-14: Cork Airport Traffic Commercial Type Distribution (Jan 2017-Aug 2018)

In terms of the non-commercial flights, most of the flights are Training flights, Cork Airport being the home of one the largest pilot training schools in Europe.

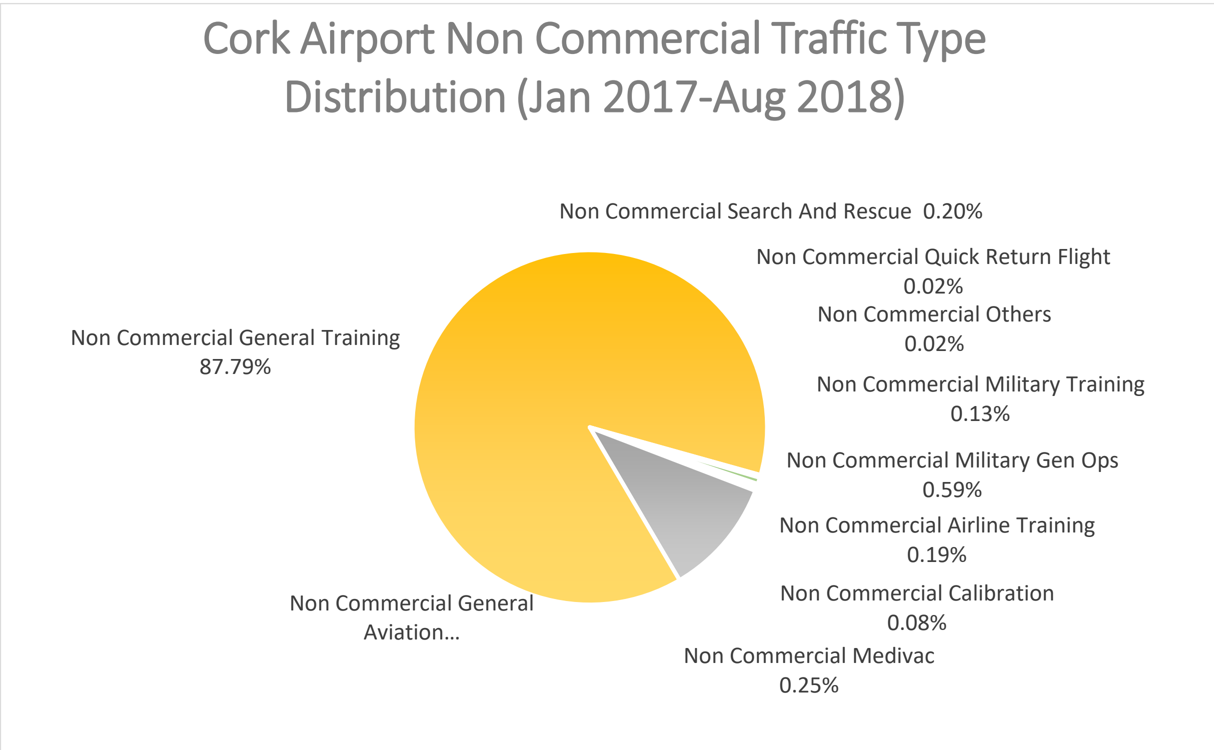


Figure 3-15: Cork Airport Traffic Non-Commercial Type Distribution (Jan 2017-Aug 2018)

Runway Analysis

Cork Airport has two runways in use, i.e. the main runway 16/34 and the cross runway 07/25. The main runway is 16/34 and it is used in more than 90% of the operations.

Table 3-1: Cork Airport Runway Usage (Jan 2017-Aug 2018)

	Total Traffic (Jan 2018 -Aug 2018)	% Usage
Main runway 16/34	66,327	90.9%
Cross runway 07/25	4,029	5.5%
Helicopter movements	2,441	3.3%
TBC	158	0.2%
	72,955	100.0%

3.4 Summary on airport analysis

Shannon and Cork airports are small to medium sized airport, with various traffic ranging from training flights to international transatlantic ones. The hourly traffic distribution shows that traffic distribution for both airports includes two traffic peaks, morning and evening, which might lead to air traffic controller workload. For instance, the morning peak hour 9-11 am has an average of 40 departures and arrivals/hour. This will mean an exponential increase of workload for any controller. Moreover, given the traffic mix (a lot of unscheduled flights), even with a lot of planning the peak traffic issues might not be easily solved as there would be too much traffic variability to account for.

Given the traffic distribution, traffic mix, and runway usage analysis, the most important aspect of multiple remote tower is the ability of the ATCO to manage a high workload induced by the traffic at peak hours.

4. Hazard Identification and Initial Analysis

Section 2.1 Remote Tower Concept of Operations presents the concept of operations for single and multiple remote tower operations for both airports, Shannon and Cork.

Understanding the operational environment and the concept of operations represents the foundation for the hazard identification process. Therefore, this information is used as an input in the brainstorming process.

The hazard identification process focuses on the multiple remote tower operations, i.e. one ATCO with two airports. The aim is to identify the hazards that are a direct consequence of an ATCO having to build and maintain his/her situation awareness for both aerodromes simultaneously. This represents Step 2 of Figure 1-2.

The objective of the Hazard Identification and Analysis process is to identify all hazard associated with operating in a multiple tower scenario. Therefore, all hazards existent in single remote tower are excluded.

Given the different technical solutions and the focus on continuously improving the quality and reliability of the screens, radar displays, electronic flight strips etc. it is decided by the group not to consider the hazards associated with the quality of the visual presentation.

For instance, the issues associated with the quality of the video presentation (quality, latency, update rate) or any aspect related to technical capabilities of the remote tower technologies are not included. While it is recognised that the technical details of the remote tower are important, these issues are also present in a single remote tower scenario. It is considered that the technology is available and appropriate to satisfy the requirements of the multiple operations e.g.:

- Remote Tower Module for multiple operations must be adequate to allow the air traffic controller to provide ATS to all aerodromes under his/her control from the same place. It should be designed as such to minimize the workload of ATC by using integrated systems while also providing a very clear way for the ATC to know which airport is controlled by which component.

- The video presentation shall allow the ATC to simultaneous monitor both aerodromes, thus complying with the ICAO Doc 4444 provisions (International Civil Aviation Authority, 2016).

The Hazard Identification and Analysis process follows the steps presented in the process diagram described in Figure 4-1 below.

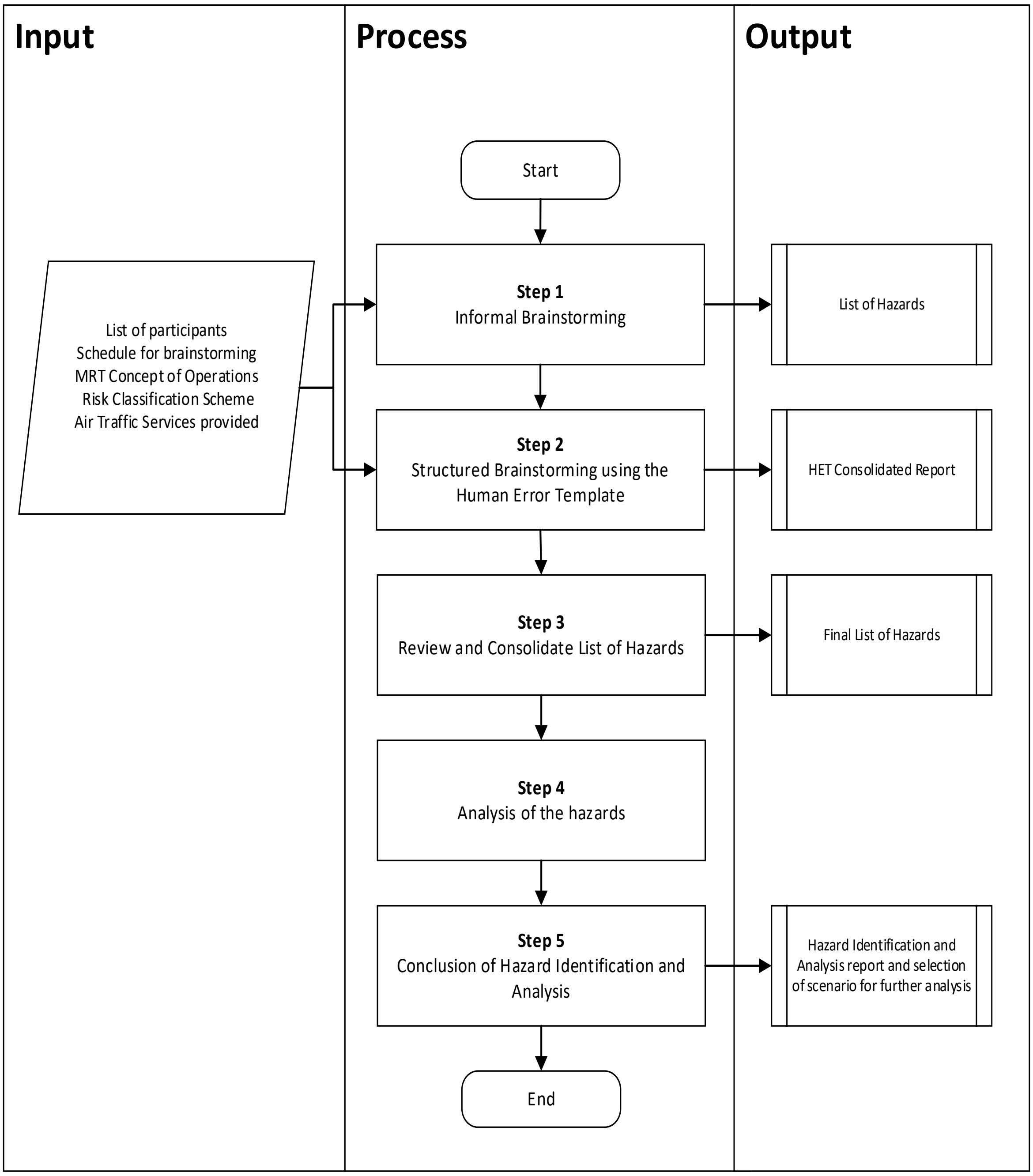


Figure 4-1: Multiple Remote Tower Hazard Identification and Analysis Process Overview

Process Input

The input for the Hazard Identification and Analysis Process is detailed in Table 4-1 below.

Table 4-1: Hazard Identification and Analysis Process Input

<table>
<tr><th>Input</th><th>Description</th></tr>
<tr><td>Participants</td><td>
The brainstorming sessions are organised with the help of air traffic controllers, ATM experts and safety experts.
The participants are selected to ensure a balance between expertise and diversity of background to benefit the brainstorming activity.
<table>
<tr><td></td><td colspan="4">Expertise</td></tr>
<tr><td></td><td>Air Traffic Control</td><td>Engineering</td><td>Safety Management</td><td>Remote Tower</td></tr>
<tr><td>Participant 1</td><td>Yes</td><td>No</td><td>No</td><td>No</td></tr>
<tr><td>Participant 2</td><td>Yes</td><td>No</td><td>Yes</td><td>Yes</td></tr>
<tr><td>Participant 3</td><td>No</td><td>Yes</td><td>Yes</td><td>No</td></tr>
<tr><td>Participant 4</td><td>Yes</td><td>Yes</td><td>No</td><td>No</td></tr>
<tr><td>Participant 5</td><td>Yes</td><td>No</td><td>Yes</td><td>No</td></tr>
<tr><td>Participant 6</td><td>Yes</td><td>No</td><td>Yes</td><td>Yes</td></tr>
<tr><td>Participant 7</td><td>No</td><td>Yes</td><td>Yes</td><td>No</td></tr>
<tr><td>Participant 8</td><td>Yes</td><td>Yes</td><td>No</td><td>No</td></tr>
<tr><td>Moderator</td><td>No</td><td>Yes</td><td>Yes</td><td>Yes</td></tr>
</table>
</td></tr>
<tr><td>Schedule</td><td>There are 2 hazard identification sessions, each followed by a debrief and review of compiled report.</td></tr>
<tr><td>Reference Documents</td><td>
The following documents are used in the Hazard Identification and Analysis process:

Multiple Remote Tower Concept of operation provided in Chapter 3 Section 3.1.
Shannon and Cork Operational Environment Overview and Air Traffic Services provided in Chapter 3 Sections 3.2 and 3.3.
Forms for the Structured Brainstorming activities as per Appendix C Notes from the Hazard Identification and Initial Analysis Human Error Template.
Risk Classification Scheme as per IAA Severity Classification Scheme.
List of Hazards from SESAR Remote ATS Safety Assessment as per Appendix D List of Hazards from SESAR Safety Assessment.

</td></tr>
</table>

Step 1: Informal Brainstorming Process and Results

The first step of the Hazard Identification process involved an informal brainstorming session. All participants are requested to list hazards that could be associated to the multiple aerodrome control. The hazards identified are listed in Table 4-2 below.

Table 4-2: Consolidated list of hazards associated with Multiple Remote Tower resulting from informal brainstorming

Hazard Number	Description
Hazard 1	ATC is confused and cannot identify the aircraft/vehicle under his/her control (e.g. simultaneous transmissions on the frequency).
Hazard 2	ATC does not detect in time conflicts on one airport by being busy managing traffic at the other airport.
Hazard 3	High ATC workload due to additional tasks and aircraft under his/her control.
Hazard 4	ATC confuses the aircraft under his/her control and gives the instruction to the wrong aircraft.
Hazard 5	ATC has to manage multiple arrivals and/or departures simultaneously.
Hazard 6	ATC inputs to wrong airport (e.g. update EFS on the wrong airport, update MET info etc).

Step 2: Structured Brainstorming Process and Results

Human Error Template with an associated risk assessment matrix, as presented below is used to identify a list of hazards associated with Multiple Remote Tower. See notes in Appendix C Notes from the Hazard Identification and Initial Analysis Human Error Template.

Human Error Template (HET) is a checklist approach and comes in the form of an error template and is used in the brainstorming process. The error taxonomy used is comprehensive as it is based on human error identification methods (Stevenage & Stanton, 1998) (Stanton, et al., 2006). The HET technique works by indicating which of the HET error modes are credible for each task step, based upon the judgment of the subject matter experts. The HET error taxonomy consists of twelve error modes, presented below:

- Fail to execute
- Task execution incomplete
- Task executed in wrong direction

- Wrong task executed
- Task repeated
- Task executed on wrong interface element
- Task executed too early
- Task executed too late
- Task executed too much
- Task executed too little
- Misread information
- Other

To assess the failure modes described above, a matrix is constructed with the vertical-axis assigned as 'likelihood', while the error 'criticality' index is placed on the horizontal-axis. Likelihood and criticality are combined through a multiplication process (likelihood x criticality) to give a Pass (Green) or Caution (Red).

Likelihood		Low 1	Medium 2	High 3
	Low 1	1	2	3
	Medium 2	2	4	6
	High 3	3	6	9
	Criticality			

Figure 4-2: The likelihood and criticality matrix with the Pass and Caution regions respectively highlighted in green and red.

The formal brainstorming is performed using this method because compared to the EU 1035/2011 (European Union, 2011) Severity definitions, this is a very easy and straightforward method of assessing risk, especially for people with no safety background. It is simple to learn and use, requiring very little training and it is also designed to be a convenient method to apply in hazard identification and assessment.

All "Caution" items are further reviewed and analysed in Step 4: Analysis of the Hazards.

All participants have completed the HET. The results presented Appendix C Notes from the Hazard Identification.

Step 3: Review and consolidation of the Multiple Remote Tower hazard list and analysis of the hazards

This step involves gathering together all the relevant hazards which is further analysed in Step 4. This hazard list is obtained by reviewing and consolidated the list of hazards resulted from the initial non-structured hazard identification session and the hazards identified by utilising the HET.

Table 4-3 is a summary of the hazards identified which have the worst most credible effects for multiple remote tower.

Table 4-3: Consolidated list of hazards associated with Multiple Remote Tower

Hazard Number	Description
Hazard 1	ATCO forgets to perform the cross check of the second airport.
Hazard 2	Scanning one aerodrome's OTW/RDP thinking is the other one.
Hazard 3a	Instruction given on wrong frequency (another airport than intended).
Hazard 3b	Incorrect instruction (different than intended) given on wrong frequency (another airport than intended).
Hazard 4	ATCO switches off airport visual aids from the wrong airport.
Hazard 5	ATCO forgets to turn on the airport visual aids.
Hazard 6	ATCO increased workload from having to control two aerodromes simultaneously.
Hazard 7	Information pertaining to the wrong airport passed to aircraft.
Hazard 8	ATCO incorrectly updates the electronic flight strip for aircraft at the other airport.

Step 4: Analysis of the Hazards

The results of the hazard analysis indicate that the expected risks associated with a particular hazard are expected to be very different, depending on the traffic situation.

Based on the discussions surrounding the specific airport operations and related traffic, it is highlighted that the more traffic presented at both airports simultaneously, the more workload is expected to increase for controllers and therefore the chance of an undesired event. Therefore, as part of the hazard analysis presented below, both simultaneous and in sequence traffic.

In sequence is defined as: *"Where the spacing between two aircraft arriving or departing at Cork and Shannon airports is equal to or more than the spacing which would be required if the two aircraft are landing or departing at the same airport. "* (Irish Aviation Authority, 2016)

Simultaneous movements are defined as: *"Where the spacing between two aircraft arriving or departing at Cork and Shannon airports is less than the spacing which would be required if the two aircraft are landing or departing at the same airport."* (Irish Aviation Authority, 2016)

The following sections present an in-depth analysis of these hazards, with detailed on the worst credible effect and sources for these hazards.

IAA Severity Classification Scheme

The severity classification scheme as per the EU Regulation 1035/2011 (European Union, 2011) is used to deduct the risks associated with the multiple remote tower operations. Both the severity class and probability are deducted using subject matter expertise.

Table 4-4: Severity Classes as per EU 1035/2011

SEVERITY CLASS	Class 1	Class 2	Class 3	Class 4	Class 5
ATS Failure Conditions - Effect on ATCO. (Assumes that failure occurs suddenly, and without warning)	Inability to provide any degree of Air Traffic Control in one or more airspace sectors for a significant period of time.	Ability to maintain Air Traffic Control is severely compromised within one or more airspace sectors for a significant period of time.	Ability to maintain Air Traffic Control is impaired within one or more airspace sectors for a significant period of time.	Ability to maintain Air Traffic Control is not impaired; however, there is a lowering of risk margins. The situation needs to be reviewed for the application of contingency measures if the condition prevails.	No immediate effect on safety

Table 4-5: Repeatability Classes as per EU 1035/2011

Frequency			
Qualitative Frequency	Qualitative Frequency Definition	Quantitative Frequency Definition	Rate per Sector
Frequent	Likely to occur in a sector during a month.	$P_s > 10^{-3}$	More than 10 per year.
Probable	Likely to occur several times in a sector during a year.	$10^{-3} \geq P_s > 10^{-4}$	Up to 10 per year.
Occasional	Likely to occur in a sector during a year.	$10^{-4} \geq P_s > 10^{-5}$	Up to 1 per year.
Remote	Unlikely to occur in sector during a year.	$10^{-5} \geq P_s > 10^{-6}$	Up to 1 in 10 years.
Improbable	Very unlikely to occur in a sector during a year.	$10^{-6} \geq P_s > 10^{-7}$	Up to 1 in 100 years.
Extremely Improbable	Extremely unlikely to occur in a sector during a year.	$P_s \geq 10^{-7}$	Up to 1 in 1000 years.

Table 4-6: Risk Classification Matrix

Frequency: P_s (Frequency per operational hour per sector)		**Risk Classification**			
		Severity Class			
		4	**3**	**2**	**1**
Frequent	$P_s > 10^{-3}$	C	A	A	A
Probable	$10^{-3} \geq P_s > 10^{-4}$	D	B	A	A
Occasional	$10^{-4} \geq P_s > 10^{-5}$	D	C	B	A
Remote	$10^{-5} \geq P_s > 10^{-6}$	D	D	C	B
Improbable	$10^{-6} \geq P_s > 10^{-7}$	D	D	D	C
Extremely Improbable	$P_s \geq 10^{-7}$	D	D	D	D

The risk classification matrix presented above highlights 4 types of possible risks:

- Risk **A**, determined intolerable, and if any present and unable to lower with any current mitigations, the new system/change cannot be implemented
- Risks **B** and **C**, determined tolerable but must be monitored and accepted prior to implementations

Risk **D**, no safety effect, tolerable.

Hazard 1: ATCO forgets to perform the cross check of the second airport

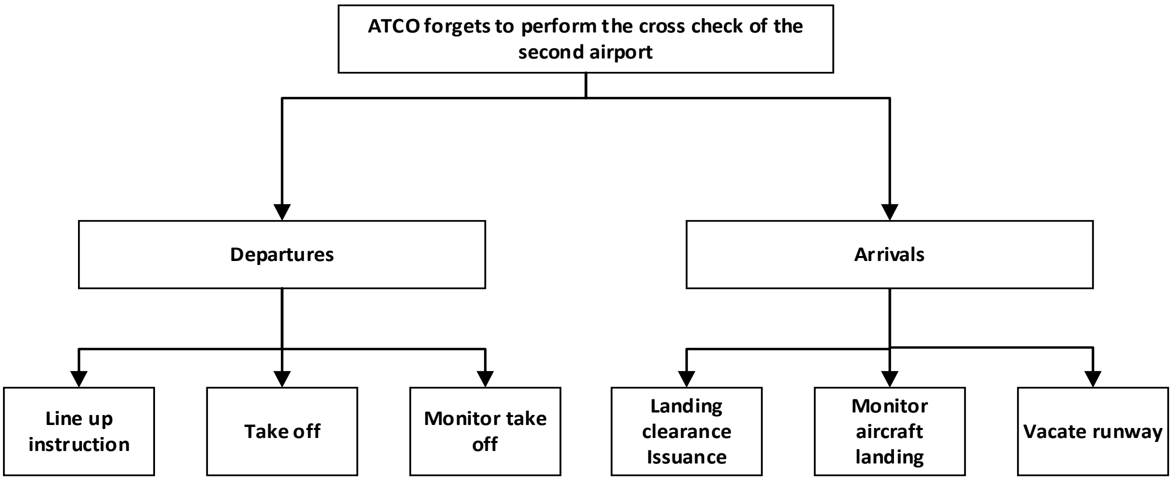


Figure 4-3: Hazard 1: ATCO forgets to perform the cross check of the second airport

In this hazard, the ATCO does not perform the cross check of the second airport. The most important phases when ATCO must cross check the other airport are considered as active departures and arrivals. All of these activities are increasing the level of the risk if they are occurring in the proximity of the active runway.

For departures, the most important phases where cross checks are considered as being necessary are when issuing a line-up or take-off clearance and consequently monitoring the take-off roll. For arrivals, issuance of landing clearance, monitoring of the landing and confirmation of runway vacate are considered of interest.

While it is important to cross check the second airport constantly, it is acknowledged that in the absence of traffic at the second airport, the most credible effect is a delay in situational awareness. Therefore, the risk for this hazard is increasing when there is active traffic in the second airport. As for any simultaneous arrivals or departures, there is an increased risk of runway conflicts, or non-detection of thereof (e.g. runway excursion happened and is undetected).

Worst credible effect	Estimated Risk
Runway Incursion/Undetected runway accident	Severity: Class 1 Frequency: Occasional **Risk Classification: A**

It is estimated that the worst credible effect in relation to lack of airport monitoring at critical phases of flight represents an undetected runway accident, e.g. runway excursion or controlled flight into terrain.

> *Note: The ATCO early/late/incorrect/incomplete/not checking the OTW for one of the airports is considered out of scope, as this is a pre-existing hazard for single remote tower operation.*
>
> *While it is acknowledged that, depending on the traffic situation, there might be an increased risk associated with these hazards, the worst hazard is chosen and detailed above.*

Hazard 2: Scanning one aerodrome's OTW/RDP thinking is the other one

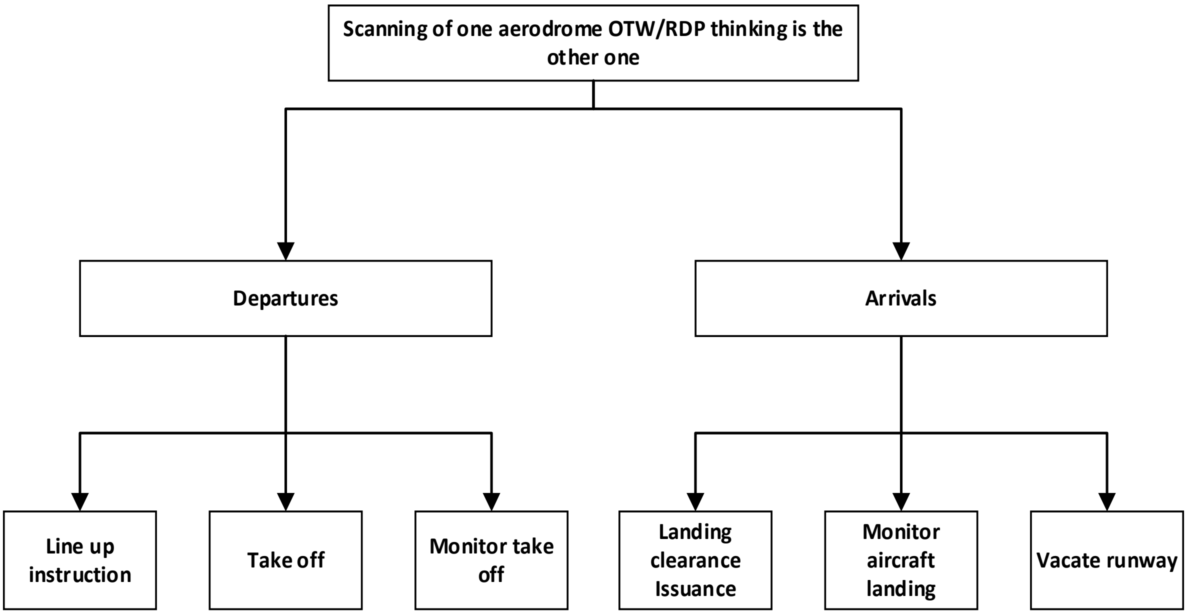


Figure 4-4: Hazard 2: Scanning one aerodrome's OTW/RDP thinking is the other one

In this hazard, the ATCO performs the necessary airport OTW/RDP scanning for the incorrect airport.

In ground operations that do not involve the runway, scanning the wrong airport is expected to result, in the most credible circumstance, in a delayed situational awareness. Therefore, those phases of flight are not included in the diagram above.

In the situations presented in the diagram above, such as issuance of line up or landing instructions, the ATCO might inadvertently clear an aircraft to the runway while the runway is either occupied or an aircraft is about to land.

It is realistic, however, to expect that the aircraft, in most situation, monitors the frequency and be aware of traffic in its vicinity. Even so, it is important that the remote tower CWP enables an easy distinction between the two aerodromes (different colours, different taxiway names, ground indications etc.) to lower the probability for confusion.

Worst credible effect	**Estimated Risk**
Runway Incursion/Undetected runway accident	Severity: Class 1 Frequency: Occasional **Risk Classification: A**

It is estimated that the worst credible effect in relation to lack of airport monitoring at critical phases of flight represents an unauthorized presence on the runway, i.e. a runway incursion which might result, depending on the situation into a ground collision.

Note: Early/late/incorrect/incomplete/no scanning of the correct aerodrome are considered as out of scope as they are pre-existing hazards related to single airport operations.

While it is acknowledged that, depending on the traffic situation, there might be an increased risk associated with these hazards, the worst hazard is chosen and detailed above.

Hazard 3: Switched Instruction to aircraft

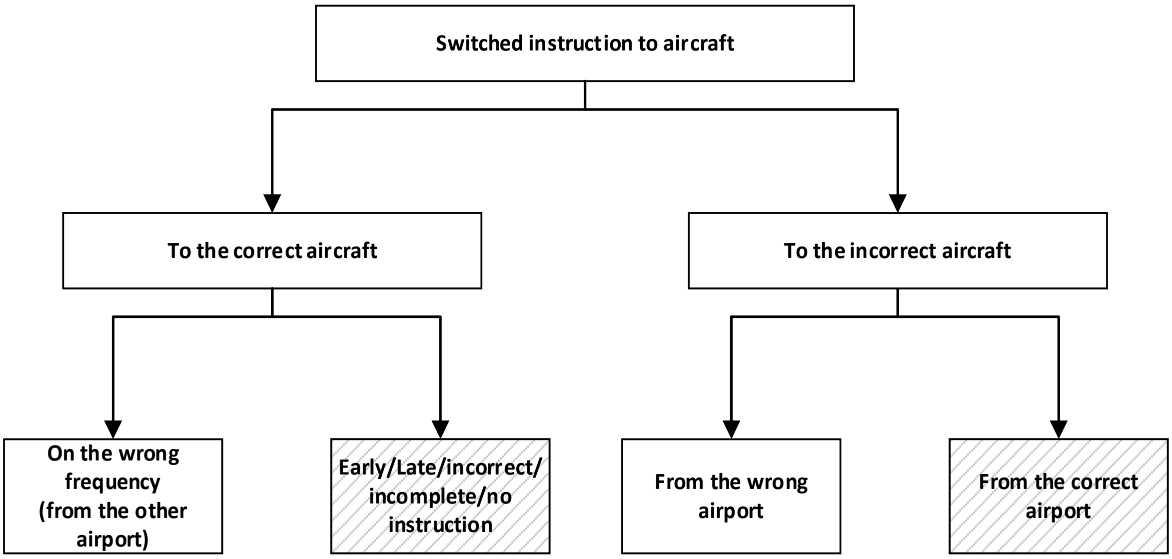


Figure 4-5:Hazard 3: Switched Instruction to aircraft

This hazard is referring to ATCO instruction to aircraft, for the correct/incorrect aircraft.

Hazard 3a: Instruction given on wrong frequency (another airport than intended)

The ATCO might provide the correct instruction to the correct aircraft on the other airport frequency. In this case, the SME has indicated that the worse credible effects are increase RT workload (aircraft might call again, ATCO will have to issue correction at the wrong airport and re-issue clearance to the correct aircraft), or Hearback/Readback error (in the case of another aircraft from the wrong airport responds to the instruction) resulting in a runway incursion/collision.

Worst credible effect	**Estimated Risk**
Runway Conflict	Severity: Class 1 Frequency: Probable **Risk Classification: A**

Hazard 3b: Incorrect instruction (different than intended) given on wrong frequency (other airport than intended)

In case an instruction is given to a wrong aircraft, multiple tactical incidents can occur, depending on the phase of flight and surrounding operational situation, e.g. taxiway conflict, taxi route deviation or, incorrect gate information to the aircraft etc.

The hazard probability and severity increase when there is another aircraft with the same intention at the wrong airport as the aircraft is more likely to follow an instruction if it fits their expectation, e.g. if a landing clearance is issued to the wrong aircraft during simultaneous approaches at both airports and lands when runway is occupied.

Worst credible effect	**Estimated Risk**
Runway Conflict	Severity: Class 1 Frequency: Probable **Risk Classification: A**

Note: Late/early/incorrect/incomplete/no instruction to correct aircraft represent pre-existing hazards in single operations. Same applies to the incorrect instruction to aircraft from the same airport.

While it is acknowledged that, depending on the traffic situation, there might be an increased risk associated with these hazards, the worst hazard is chosen and detailed above.

Hazard 4: ATCO switches off airport visual aids from the wrong airport

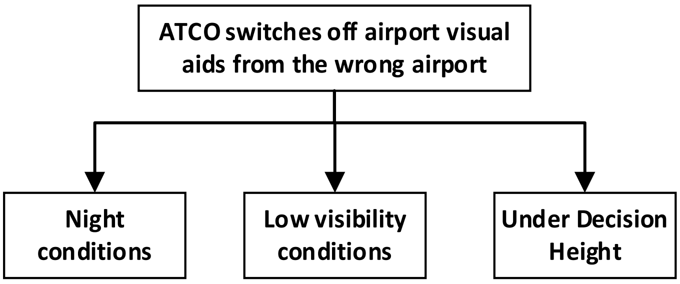


Figure 4-6: Hazard 4: ATCO switches off airport visual aids from the wrong airport

In this hazard scenario, the ATCO inadvertently switches off the wrong airport lighting at the wrong airport (in particular, runway and approach lights). This is a possible hazard as current procedure to switch off airport lighting when no movement is expected at that airport.

As per the Figure 4-6 above, in either night conditions or low visibility conditions, if the runway and approach lights are switched off and an aircraft is on approach, below decision height, the consequence of the landing with no visual aids can vary from runway excursion to controlled flight into terrain.

The airport lighting panels must therefore be designed to ensure that a complete and obvious delimitation between the two aerodromes is achieved. Another option would be to amend the airport procedures to ensure the lights are on at time or install lights that automatically activate when an aircraft is approaching a runway for arrival or departure.

Worst credible effect	**Estimated Risk**
Runway Collision, Runway Excursion/Control Flight into Terrain	Severity: Class 1 Frequency: Occasional **Risk Classification: A**

It is estimated that the worst credible effect in relation to turning off the airport lights as per the scenario presented above is a Runway Excursion/Control Flight into Terrain.

Note: ATCO turning off the lights of the correct airport. This is considered a pre-existing hazard for single remote tower.

While it is acknowledged that, depending on the traffic situation, there might be an increased risk associated with these hazards, the worst hazard is chosen and detailed above.

Hazard 5: ATCO forgets to turn on the airport visual aids

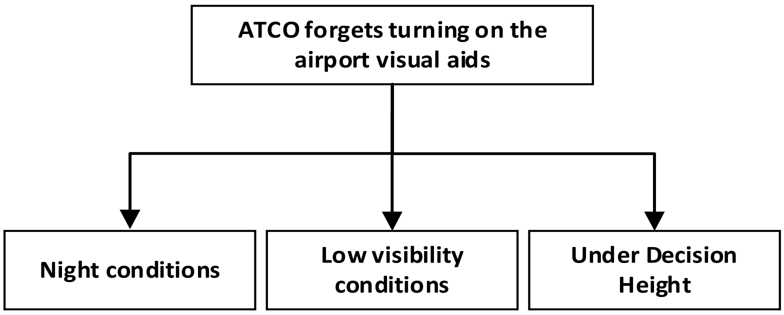


Figure 4-7: Hazard 5: ATCO forgets to turn on the airport visual aids

In this hazard scenario, the ATCO forgets to turn on the airport lighting. This is a possible hazard as current procedure are to switch off most of the airport lighting (runway, approach and taxiway lights), when no movement is expected at that airport.

In either night conditions or low visibility conditions, if the runway lights are not activated, an aircraft on approach do not proceed below decision height and execute a missed approach.

Compared to Hazard 4, this is most likely to occur in simultaneous operations, where the ATCO is busy responding to aircraft from the other airport and forgets to switch on the lighting.

Worst credible effect	**Estimated Risk**
Missed approach	Severity: Class 2 Frequency: Occasional **Risk Classification: B**

It is estimated that the worst credible effect in relation to turning off the airport lights as per the scenario presented above is a Missed approach

> *Note: ATCO turning off the lights of the correct airport. This is considered a pre-existing hazard for single remote tower.*
>
> *While it is acknowledged that, depending on the traffic situation, there might be an increased risk associated with these hazards, the worse hazard is chosen and detailed above.*

Hazard 6: ATCO increased workload from having to control two aerodromes simultaneously

Figure 4-8: Hazard 6: ATCO increased workload from having to control two aerodromes simultaneously

This hazard is in relation to the additional tasks induced by multiple remote tower operations. Depending on the reference airport, the additional tasks can be induced by either Shannon or Cork, and by the simultaneous operations.

The SME are expecting that the additional tasks related with the extra airport to not be directly translating to a workload equal to summation of the estimated workload for each individual airport.

$$Workload_{Multiple\ Remote\ Tower} = Workload_{Shannon} + Workload_{Cork} + Workload_{simultaneous}$$

The unknown additional workload induced by the addition of the two airports (*Workload* $_{simultaneous}$) is currently unquantified and it can influence the ATCO workload to an unacceptable level. Some influencing factors identified are:

- Simultaneous transmission and monitoring on two airport frequencies

- Simultaneous runway movements, arrival or departures, which might result in an ATCO having to monitor, for instance, one arrival in Shannon and departure in Cork simultaneously.

- Multitasking associated with building and maintaining situational awareness for the two airports, i.e. continuous switch between the two requires additional time to restore and update the ATCO situational awareness.

Worst credible effect	**Estimated Risk**
Accident	Severity: Class 1 Frequency: Frequent **Risk Classification: A**

The high density of traffic and dynamic aircraft manoeuvres in the terminal airspace increases ATCO's perceived workload, as controllers face additional difficulties which decreases controller's performance and create safety concerns. It is estimated that the worst credible effect in relation to having to perform additional tasks is a high/intolerable workload.

One of the most commonly used measures of ATCO's perceived workload is NASA Task Load Index (Hart & Staveland, 1988). The cognitive assessment tool of NASA-TLX is a subjective assessment method that use self-reported rating scores at a given moment in time. The advantage of these self-reported workload rating is the ease of application. Workload can negatively affect ATCOs' performance and increase the error of operation. (Wickens, 1988) define workload as the load imposed on the limited information processing resources of the unaided (without assistance of automation) human operator described as the "baseline" or "manual" condition. This workload load can be imposed from two qualitatively distinct sources, the single task difficulty of the task that might otherwise be automated, and the multitask load in which the baseline (vs. automated) task is performed.

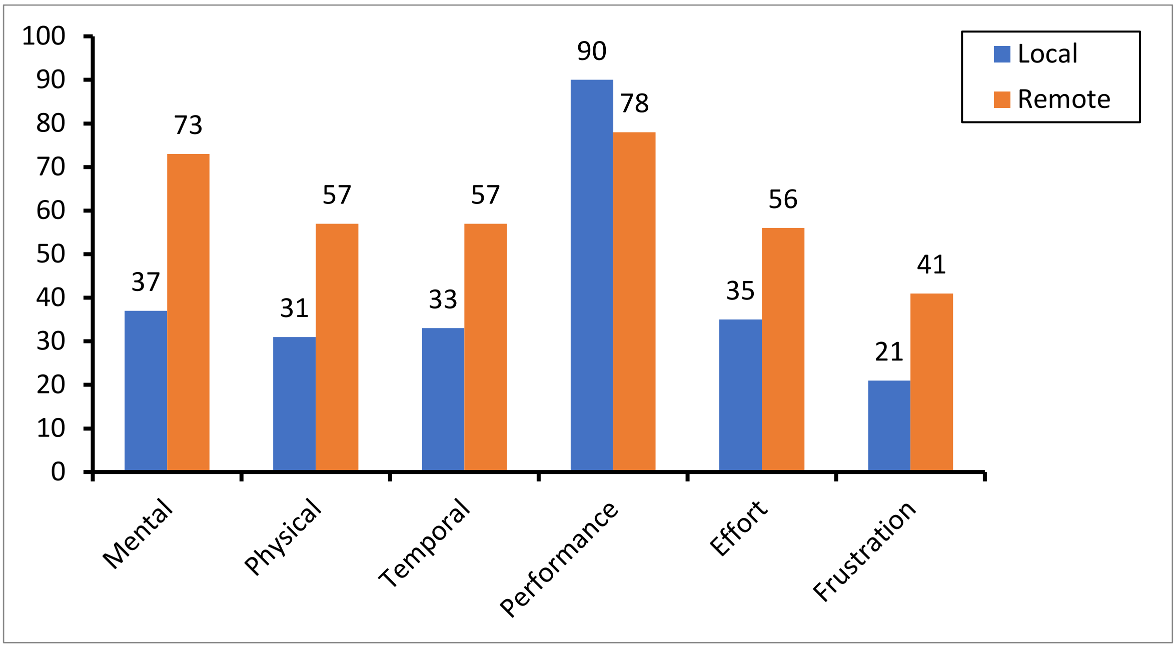


Figure 4-9: ATCO's perceived workload related to two B-737 departing from CORK in sequence compared to multiple remote tower operations of departure from R-35 CORK and R-24 Shannon simultaneously by NASA-TLX

The results of the IAA live trials, it is highlighted that the perceived workload is overall increasing for the multiple remote tower (Irish Aviation Authority, 2016).
There is a trend of increasing mental demand (37 vs 73), physical demand (31 vs 57), temporal demand (33 vs 57), effort (35 vs 56), and frustration (21 vs 41) by multiple remote tower operations compared to local tower operations. Furthermore, the performance is decreasing (78 vs 90) by multiple remote tower operations when compared to local tower operations.

The results of the trials are discussed among the participants and all have agreed that workload increase can have a high impact on operations and ATCO. All have agreed that this hazard can have the worst consequences of all hazards identified and can drive a "go" or "no go" decision to implement multiple remote tower.

Unfortunately, this hazard is also very hard to assess as workload is not influenced by specific and tangible factors (e.g. frequency of aircraft, frequency of instructions issues, type of traffic etc.), but it is also depended on personal factors (e.g. preference or familiarity with particular operations).

Hazard 7: Information pertaining to the wrong airport passed to aircraft

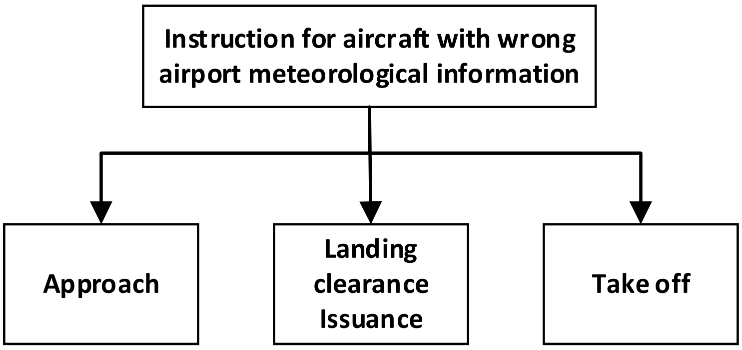


Figure 4-10: Hazard 7: Information pertaining to the wrong airport passed to aircraft

In this hazard scenario, the ATCO provides erroneous airport information to the aircraft.

In the case of non-runway specific operations e.g. clearance delivery or taxiing, the provision of incorrect information (incorrect active runway or weather conditions) may result in increased workload for flight crews or a tactical conflict on the ground.

In a worse scenario, an aircraft on approach is given real time meteorological information from the wrong airport which could result in a pilot executing an approach / landing / take-off with incorrect wind information or the pilot could assume good visibility during low-visibility conditions.

Regularly updated ATIS at each airport acts as a barrier against the hazard presented above, yet it is expected that the controller provides the most up to date information to the aircraft.

Worst credible effect	**Estimated Risk**
Runway Excursion/ Controller Flight Towards Terrain	Severity: Class 1 Frequency: Occasional **Risk Classification: A**

It is estimated that the worst credible effect in relation to turning off the airport lights as per the scenario presented above is a runway excursion.

Note: Early/late/incorrect/incomplete/no essential traffic information hazards are identified as part of the hazard identification process and considered pre-existing hazards for single remote tower.

While it is acknowledged that, depending on the traffic situation, there might be an increased risk associated with these hazards, the worse hazard is chosen and detailed above.

Hazard 8: Incorrect Electronic Flight Strip (EFS) updated for aircraft at wrong airport

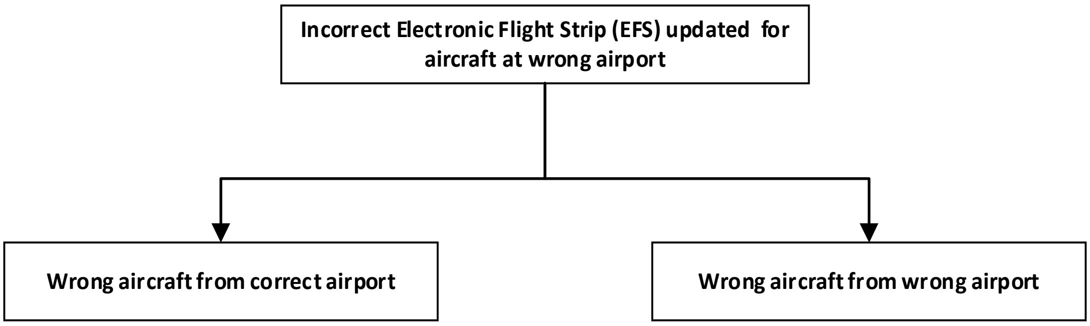


Figure 4-11: Hazard 8: Incorrect Electronic Flight Strip (EFS) updated for aircraft at wrong airport

In this hazard, the ATCO updates the flight strip for an aircraft on another aircraft from the other airport.

In this scenario, the risks associated with this hazard are also dependent on the similarity between the two airports' operational environment and the phase of flight for the aircraft.

If EFS is incorrectly updated at the end of a flight (e.g. aircraft is recorded as parked) then the other active flight's EFS disappears from the system and it is very hard for the air traffic controller to stop or correct the error.

Worst credible effect	**Estimated Risk**
Degradation of situational awareness	Severity: Class 2 Frequency: Probable **Risk Classification: A**

It is estimated that the worst credible effect is reduced ATCO Situational Awareness as a result of the loss of flight strip information.

Note: Incorrect/incomplete/no update of the EFS for the correct aircraft are identified as part of the hazard identification process and considered pre-existing hazards for single remote tower.

While it is acknowledged that, depending on the traffic situation, there might be an increased risk associated with these hazards, the worse hazard is chosen and detailed above.

Summary of Hazard Analysis

Table 4-7: Multiple Remote Tower List of Hazards and associated risks

Hazard Number	Description	Risk
Hazard 1	ATCO forgets to perform the cross check of the second airport.	Severity: Class 1 Frequency: Occasional **Risk Classification: A**
Hazard 2	Scanning one aerodrome's OTW/RDP thinking is the other one.	Severity: Class 1 Frequency: Occasional **Risk Classification: A**
Hazard 3a	Instruction given on wrong frequency (another airport than intended).	Severity: Class 1 Frequency: Probable **Risk Classification: A**
Hazard 3b	Incorrect instruction (different than intended) given on wrong frequency (another airport than intended).	Severity: Class 1 Frequency: Probable **Risk Classification: A**
Hazard 4	ATCO switches off airport visual aids for aircraft from the wrong airport.	Severity: Class 1 Frequency: Occasional **Risk Classification: A**

Hazard 5	ATCO forgets to turn on the airport visual aids.	Severity: Class 2 Frequency: Occasional **Risk Classification: B**
Hazard 6	ATCO increased workload from having to control two aerodromes simultaneously.	Severity: Class 1 Frequency: Frequent **Risk Classification: A**
Hazard 7	Information pertaining to the wrong airport passed to aircraft.	Severity: Class 1 Frequency: Occasional **Risk Classification: A**
Hazard 8	ATCO incorrectly updates the electronic flight strip for aircraft at the other airport.	Severity: Class 2 Frequency: Probable **Risk Classification: A**

Step 5: Conclusion of the Hazard Identification and Analysis

This hazard analysis process has identified that, before implementing multiple remote tower, multiple aspects of operations must be considered.

In terms of hazards of interest for further analysis, the following hazards have been excluded:

- Hazard 1: ATCO forgets to perform the cross check of the second airport; this hazard is considered to be a subpart of all the other hazards, and a causal factor for triggering the other hazards.
- Hazard 2: Scanning one aerodrome's OTW/RDP thinking is the other one; as above.
- Hazard 4: ATCO switches off airport visual aids from the wrong airport; this hazard can be easily mitigated by updating the procedure that might trigger the hazard.
- Hazard 5: ATCO forgets to turn on the airport visual aids; as above.
- Hazard 6: ATCO increased workload from having to control two aerodromes simultaneously; this hazard can have a high impact on operations and ATCO, and it can have the worst consequences of all hazards identified and can drive a "go" or "no go" decision to implement

multiple remote tower. Unfortunately, this hazard is also very hard to assess as workload is not influenced by specific and tangible factors (e.g. frequency of aircraft, frequency of instructions issues, type of traffic etc.), but it is also depended on personal factors (e.g. preference or familiarity with particular operations).

- Hazard 7: Information pertaining to the wrong airport passed to aircraft; this is a sub-hazard of Hazard 3.

- Hazard 8: ATCO incorrectly updates the electronic flight strip for aircraft at the other airport. The result of the hazard is reduced situation awareness, which as in the case of hazard 6 above it is very hard to assess.

Hazard 3 has been selected for further analysis and modelling. Hazard 3: Switched Instruction to aircraft also constitutes the subject of further analysis. Aircraft instructions are becoming more challenging when the ATCO must give instruction for aircraft located at two airports. Moreover, the aircraft on ground are unaware of the traffic situation at the other airport and are less likely to correct an incorrect instruction if it also expecting a similar instruction (e.g. take off instruction at Cork is given to aircraft waiting for line up clearance in Shannon; this instruction is not heard in Cork, the aircraft contacts the ATCO who has to correct and update clearance for both airports). The risks associated with this hazard are ranging from hearback/readback errors to runway conflicts.

5. Construct Operational Scenario

The next step from the Hazard Identification and Analysis is the construction of scenarios to further analyse the chosen hazard. This represents Step 3 of the Figure 1-2.

As described in the previous chapter, Hazard Identification and Initial Analysis, the hazard chosen for further analysis is Hazards 3a Instruction to correct aircraft on the other airport's frequency and Hazard 3b Instruction to incorrect aircraft from the incorrect airport.

This hazard has been further analysed with the same participants in the Hazard Identification and Analysis team, to deduct a scenario where these hazards are expected to have worse consequences if encountered.

All the elements of the scenario described below have been discussed with the participants in the Hazard Analysis session. As a result, the elements selected in blue have been selected for the final scenario.

Table 5-1: Multiple Remote Tower Scenario Development Parameters

Element No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Category	Aerodrome		ATCO	Communication System			Operational Context						ATCO		Pilot Shannon Lined up	Pilot Cork Lined up	Pilot Cork Landing
Variable	Number of aerodromes	Aerodrome Safety Nets	Number of ATCO	Type of ATCO communications	Frequency occupation Shannon Airport	Frequency occupation Shannon Airport	Location of aircraft on Shannon Airport	Location of first aircraft on Cork Airport	Location of second aircraft on Cork Airport	Simultaneous operations	Weather	Callsign Similarity	Type of Clearance	ATCO Failure Modes	Pilot Failure Modes	Pilot Failure Modes	Pilot Failure Modes
Dimensions	2	Stopbars	1	Couple	Peak hour	Peak hour	Gate	Gate	Gate	Yes	Good weather	Very Similar	Conditional clearance	ATCO issues clearance on wrong frequency. The clearance is completely incorrect. *E.g. ATCO clears an aircraft to pushback instead of take-off*	Pilot Shannon does not challenge ATCO instruction. *E.g. Pilot not sure about the clearance yet continues as instructed without challenging ATCO.*	Pilot does not challenge ATCO instruction. *E.g. Pilot not sure about the clearance yet continues as instructed without challenging ATCO.*	Pilot Cork does not challenge ATCO instruction. *E.g. Pilot not sure about the clearance yet continues as instructed without challenging ATCO.*
		A-SMGCS/ RIMCAS	2	De-coupled	Non-Peak Hour	Non-Peak Hour	Taxiway	Taxiway	Taxiway	No	Low visibility procedures	Similar	Non-conditional clearance	ATCO issues correct clearance on wrong frequency. *E.g. ATCO issues line up instruction on the incorrect frequency, using the callsign of the aircraft that was meant to receive the clearance.*	Pilot Shannon doesn't use standard phraseology when reading back the clearance.	Pilot Cork doesn't use standard phraseology when reading back the clearance.	Pilot Cork doesn't use standard phraseology when reading back the clearance.
							Departure Holding Point	Departure Holding Point	Departure Holding Point			Completely different		ATCO issues instruction on wrong frequency and uses wrong call sign (callsign of aircraft on wrong frequency). *E.g. ATCO issues line up instruction on the incorrect frequency, using the callsign of the incorrect aircraft.*	Pilot Shannon from the correct airport that is waiting for clearance delays repeating request to ATCO.	Pilot Cork from the correct airport that is waiting for clearance delays repeating request to ATCO.	Pilot Cork from the correct airport that is waiting for clearance delays repeating request to ATCO.

							Take-off	Take-off	Take-off					ATCO doesn't recognize error when pilot readback the clearance.	Pilot Shannon starts performing the instruction, sees the conflict on runway and challenges ATCO. *E.g. Pilot starts performing the instruction from ATCO and notices potential conflict.*	Pilot Cork starts performing the instruction, sees the conflict on runway and challenges ATCO. *E.g. Pilot starts performing the instruction from ATCO and notices potential conflict.*	Pilot Cork starts performing the instruction, sees the conflict on runway and challenges ATCO. *E.g. Pilot starts performing the instruction from ATCO and notices potential conflict.*
							Departure Handover	Departure Handover	Departure Handover					ATCO doesn't detect the error by looking at the screen. *E.g. The wrong aircraft has started following the instruction given by the ATCO, but the ATCO doesn't notice.*	Conflict aircraft/vehicle hears or sees the conflict and notifies ATCO. *E.g. Aircraft on final hears an aircraft being cleared to line up and notifies ATCO.*	Conflict aircraft/vehicle hears or sees the conflict and notifies ATCO. *E.g. Aircraft on final hears an aircraft being cleared to line up and notifies ATCO.*	Conflict aircraft hears or sees the conflict and notifies ATCO. *E.g. Aircraft on final hears an aircraft being cleared to line up and notifies ATCO and goes around.*
							First Contact on Approach	First Contact on Approach	First Contact on Approach								
							Approach	Aircraft on Approach	Aircraft on Approach								
							Landing (cleared to land)	Landing (cleared to land)	Landing (cleared to land)								
							Touchdown	Touchdown	Touchdown								
							Runway Vacate	Runway Vacate	Runway Vacate								

Element 1: Number of Aerodromes

The scenario contains the two aerodromes planned for multiple remote tower operations, i.e. Shannon and Cork.

Element 2: Aerodrome Safety Nets

Both aerodromes have stopbars. Neither of the aerodromes have A-SMGCS/RIMCAS.

Nevertheless, the stopbars are not in use in either airport for normal operations, just in low visibility operations.

Element 3: Number of ATCOs

The scenario involves one ATCO managing both aerodromes ground and air movements, as currently planned for multiple remote tower for these airports.

Element 4: Type of ATCO Communications

The airport frequencies can be presented to the ATCO in either coupled or decoupled way. In the decoupled scenario, the ATCO can hear RT broadcasts on both aerodromes, while the aircraft/vehicles can only hear communications that are coming from their airport. In the coupled scenario, all communications can be heard at both aerodromes.

The plan in Shannon and Cork is to use de-coupled frequencies.

Element 5: Type of Communication Frequency Occupation Shannon Airport

This scenario considers the peak period for Shannon Airport and therefore the time where the frequency is mostly used.

Element 6: Type of Communication Frequency Occupation Cork Airport

This scenario considers the peak period for Cork Airport and therefore the time where the frequency is mostly used.

Element 7: Location of aircraft on Shannon Airport

It is considered by the group that the worst-case scenario for aerodrome operations is when an aircraft is cleared to the runway when the runway is in use or expected to be in use at the point when the aircraft is lined up. In this scenario the aircraft is Shannon is going to be at the departure holding point. Other aircraft positions are not of interest, but modelled with variable “frequency occupation”

Element 8 and Element 9: Location of aircraft on Cork Airport

It is considered by the group that the worst-case scenario for aerodrome operations is when an aircraft is cleared to the runway when the runway is in use or expected to be in use at the point when the aircraft is lined up.

This scenario includes an aircraft at the Departure Holding Point in Cork airport with another one being on final approach and in a conflict with the aircraft holding. The operational situation requires the aircraft on the ground to wait for the aircraft to land and then it can depart.

The reason for choosing the conflict to occur in Cork is multifold:

- Cork has almost double the traffic than Shannon, therefore increase chances of having a conflict.
- Cork has more than 50% general aviation traffic from the biggest training school in Ireland. Student pilots tend to make more mistakes, especially phraseology related (high percentage of foreign students).
- In the last 3 years Cork has reported double the number of runway incursion more than Cork.

Other aircraft positions are not of interest but modelled with variable "frequency occupation"

Element 10: Simultaneous operations

It is considered by the participants that the most credible scenario that an aircraft follows an instruction that it is not meant for it would be only and only if it expects the same instruction itself. In other words, if an aircraft is told to line up when it is just pushing back, not only it is very likely that it catches the error in the instruction, it would be impossible for it to follow that instruction. Therefore, both aircraft that are under control have to be in the same phase of flight with the same intention. In the chosen scenario, both aircraft are holding at the departure holding point, waiting for line up clearance.

Element 11: Weather

The scenario only considers good weather at both airports since VFR traffic is not allowed in bad weather. In Cork, most flights are VFR.

Element 12: Callsign Similarity

All three scenarios are modelled, i.e. from no similarity between them (ABC 123 and XYZ 345), similar callsigns (ABC 231 and DEF 231) and very similar callsigns (ABC 123 and ABC 127). Callsign similarity definition are used from the EUROCONTROL Callsign Similarity Rules (European Organisation for the Safety of Air Navigation (EUROCONTROL), 2019).

Element 13: Type of Clearance

The controllers can give two types of clearances, normal clearances (e.g. ABC123 cleared to take off) and conditional clearances (clearance issued by an air traffic controller which does not become effective until a specified condition has been satisfied, e.g. AFTER the departing aircraft, BEHIND the landing aircraft).

A danger of misunderstanding, ambiguity or other confusion could exist in a conditional clearance, for example:

- If more than one similar aircraft (e.g. same aircraft type and same operator) are passing in front of the subject aircraft; or,

- If an aircraft is in an unfamiliar airport; or,
- If the subject aircraft is not where the air traffic controller thought (e.g. at a different runway holding point);
- the pilot might follow the wrong aircraft.

Conditional phrases, such as “behind landing aircraft” or “after departing aircraft”, are not recommended to be used for movements affecting the active runway(s), except when the aircraft or vehicles concerned are seen by the appropriate ATCO and pilot.

Conditional clearances are not used by ATCO near an active runway neither in Cork nor in Shannon, therefore for this scenario only normal clearances are considered.

Element 14: ATCO Failure Modes

The following ATCO failures are out scope of the scenario:

- ATCO issuing an ATCO issues completely incorrect clearance on the incorrect frequency is considered out of scope. For instance, ATCO clears an aircraft to pushback instead of take-off, i.e.:
    - Correct clearance: ABC123 cleared to take off RWY 12.
    - Incorrect Clearance: EIN145 cleared to pushback.

  It is considered that it is unrealistic to consider that an aircraft follows an instruction that is not in line with its expectation.
- It is also considered that if the ATCO detects the error by later looking at the remote tower screens, it would be too late to avoid the incident since it would be expected that the aircraft would have already passed the Departure holding point.

The following ATCO failures are in scope of the scenario:

- ATCO issues correct clearance on wrong frequency.

  E.g. ATCO issues line up instruction on the incorrect frequency, using the callsign of the aircraft that is meant to receive the clearance.
- ATCO issues instruction on wrong frequency and uses wrong call sign (callsign of aircraft on wrong frequency).
  E.g. ATCO issues line up instruction on the incorrect frequency, using the callsign of the incorrect aircraft.
- ATCO doesn't recognize error when pilot readback the clearance.

  E.g. The wrong aircraft has started following the instruction given by the ATCO, but the ATCO doesn’t notice the error.

Element 15: Pilot Shannon Line up Failure Modes

All Pilot Failure Modes were discussed. The following are out of scope:

- Pilot starts performing the instruction, sees the conflict on runway and challenges ATCO.

  E.g. Pilot starts performing the instruction from ATCO and notices potential conflict.

  No conflict is present in Shannon in this scenario.

- Conflict aircraft/vehicle hears or sees the conflict and notifies ATCO.

  E.g. Aircraft on final hears an aircraft being cleared to line up and notifies ATCO.

  No conflict is present in Shannon in this scenario.

- Pilot does not challenge ATCO instruction.

  E.g. Pilot not sure about the clearance yet continues as instructed without challenging ATCO.

  Not in scope since any clearance for Shannon airport will not result in a conflict.

- Pilot doesn't use standard phraseology when reading back the clearance.

  E.g. Pilot readback "Roger" instead of "Cleared for take-off RYR123"

  Not in scope since the probability of student pilots and consequently usage of non-standard phraseology is negligible.

The following are in scope for the scenario:

- Pilot from the correct airport that is waiting for clearance delays repeating request to ATCO.

  E.g. Pilot waiting for clearance not aware of the aircraft on the other frequency, therefore assuming ATCO responds soon. Pilots can be reluctant to repeat requests.

Element 16: Pilot Cork Line Up Failure Modes

All Pilot Failure Modes were discussed. The following are out of scope:

- Pilot starts performing the instruction, sees the conflict on runway and challenges ATCO.

  E.g. Pilot starts performing the instruction from ATCO and notices potential conflict.

  It is assumed that the pilot is focussed on following ATCO instruction, and therefore being focussed performing the actions. The default attitude from pilots is to follow the instructions from ATCO and not to challenge.

- Conflict aircraft/vehicle hears or sees the conflict and notifies ATCO.

  E.g. Aircraft on final hears an aircraft being cleared to line up and notifies ATCO.

This is out of scope since the runway incursion has already occurred. The situation where ATCO must be notified of conflicts from the air or ground is considered to be a complete loss of situational awareness for the ATCO and too late to stop the conflict. This is considered in for the arriving aircraft in Cork.

The following are in scope for the scenario:

- Pilot does not challenge ATCO instruction.

  E.g. Pilot not sure about the clearance yet continues as instructed without challenging ATCO.

- Pilot doesn't use standard phraseology when reading back the clearance.

  E.g. Pilot readback "Roger" instead of "Cleared for take-off RYR123"

  The probability of pilots not using standard phraseology is high in Cork airport given to more than 50% of flights are student flights.

Element 17: Pilot Cork Landing Aircraft Failure Modes

The following are in scope for the scenario:

- Conflict aircraft/vehicle hears or sees the conflict and notifies ATCO.

  E.g. Aircraft on final hears an aircraft being cleared to line up and notifies ATCO.

  This is considered to be in scope for the landing aircraft. It is expected that, if the arrival aircraft is above Decision Height, the aircraft initiates a go around.

Summary of Scenario for Modelling

The scenario based on the criteria from the Table 5-1 is presented in the Figure 5-1 below.

The ATCO is communicating with both aerodromes waiting for line-up clearance. The ATCO assessing the operational situation Shannon and Cork decides to give line up clearance for aircraft in Shannon since there is no conflicting traffic currently in an around the runway that is expected to be on the runway when the aircraft is lined up.

Nonetheless, the ATCO inadvertently either clears the right aircraft using the wrong frequency (from Cork), or worse gives the wrong aircraft the line-up clearance on the wrong frequency (Cork).

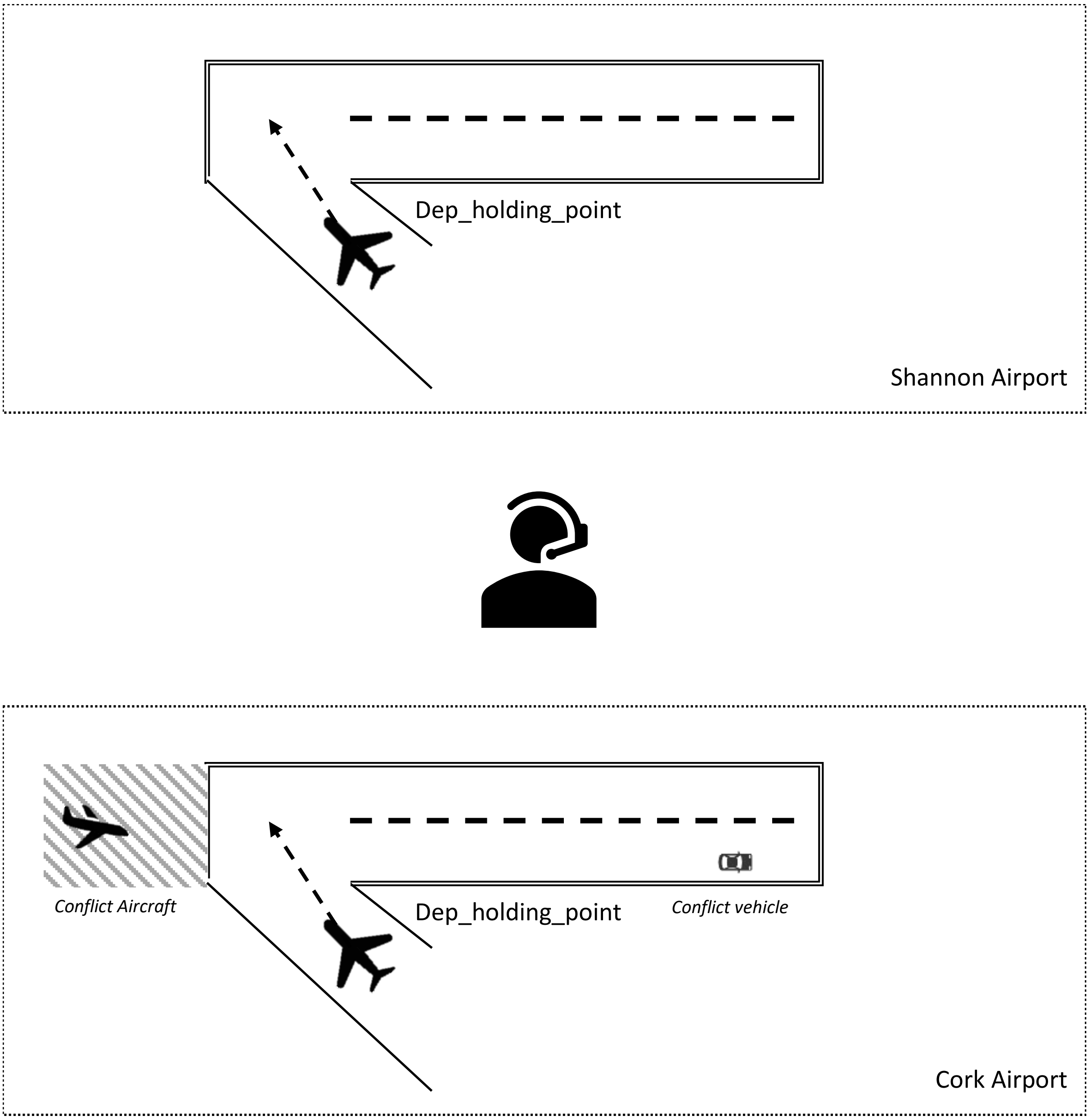


Figure 5-1: Multiple Remote Tower Scenario Diagram

6. Multi-agent Model of Multiple Remote Tower Operation

6.1 Agent based model for Multiple Remote Tower operation

Based on the information in Chapter 5, an agent-based model is constructed. This represents Step 4 of Figure 1-2.

An overview of the agents is presented in Figure 6-1 below.

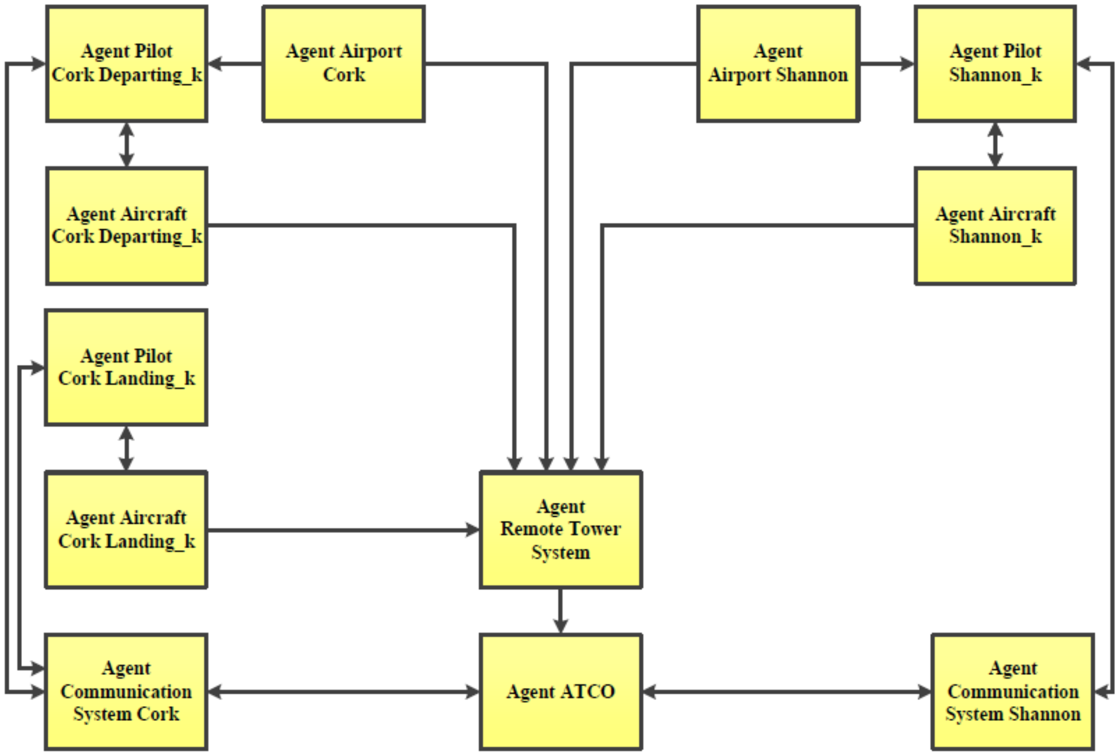


Figure 6-1: Agent based model for multiple remote tower system

The following agents were identified as relevant:

- Agent ATCO which summarises the actions that the ATCO performs when an ATCO receives a request from a pilot.
- Agent Pilot Cork Landing_k represents the Cork pilot landing at the airport.
- Agent Pilot Cork Departing_k represents the Cork pilot waiting for line up clearance at the runway departure holding point and the actions of the pilot to line up.
- Agent Pilot Shannon Departing_k represents the Shannon pilot waiting for line up clearance at the runway departure holding point and the actions of the pilot to line up.
- Agent Aircraft Cork Landing_k has been designed to recreate aircraft landing in Cork.

- Agent Aircraft Cork Departing_k has been designed to recreate aircraft departing in Cork.
- Agent Aircraft Shannon_k has been designed to recreate aircraft departing in Shannon.
- Agent Airport Cork represents the Cork airport. In this scenario, the airport is open.
- Agent Airport Shannon represents the Shannon airport. In this scenario, the airport is open.
- Agent Communication System Cork has been designed to recreate the frequency in Cork Airport.
- Agent Communication System Shannon has been designed to recreate the frequency in Shannon Airport.
- Agent Remote Tower system replicated the remote tower screens in the remote tower modules and recreates what the ATCO sees outside. It acts like an extended mind for the ATCO.

6.2 Multi-agent Situation Awareness (MASA)

Introduction

Situation awareness is defined as a dynamic state of knowledge, which discriminates between three levels (Endsley, 1995), i.e. perception of elements in the environment, comprehension of their meaning and projection of their future state.

MASA is defined as (Blom, H.A.P; Sharpanskykh, A, 2015):

$$\sigma_{t,agent\ k}^{agent_j} = SA\ of\ (non)agent_k\ at\ time\ t\ about\ (non)agent_j = \begin{pmatrix} Identity_{t,agent_k}^{agent_j} \\ State_{t,agent_k}^{agent_j} \\ Mode_{t,agent_k}^{agent_j} \\ Intent_{t,agent_k}^{agent_j} \end{pmatrix}$$

Equation 1: SA Vector in ATM (Blom, H.A.P, 2018)

$$\sigma_{t+\Delta} = f^{SA}(\sigma_t, \mu_t, \varepsilon_t)$$

Equation 2: Dynamics of SA updating (Blom, H.A.P, 2018)

where Δ= duration, μ = input and ε = stochastics. Each agent determines its own moment at which an update is made of its SA, depending on the model of the $agent_k$ and its interactions with $agent_j$.

Based on the (Blom, H.A.P, 2018), MASA can be gained, maintained or lost through three modes:

- Observation, by one agent about the state of another agent
- Communication, from received by one agent from another agent

- Reasoning, by an agent after MASA updating due to an observation or a message.

In a multiple remote tower simulation, the air traffic controller builds his/her situation awareness from multiple factors, such as airport characteristics(runway, taxiway, control zone, reporting points layout and any other operational agreements), communications (frequencies, callsigns, language, phraseology, flight information), procedures in use (taxy, take-off, approach, VFR/IFR, LVP, night operations), airport and operations planning(runway and control zone capacity), weather (QNH, wind direction and speed, cloud coverage, temperature, dew point) and traffic monitoring activities (position, track altitude, separation, performance, trend, clearance status).

In this simulation, the following are considered when building the MASA:

- Communications, i.e. the frequencies, the callsigns of the aircraft and how similar they are to each other, phraseology language and experience of the pilots (in Cork since 50% of the flights are students training).
- Airport characteristics, in particular the orientation of the remote tower cameras. Most of the cameras are orientated as such to allow a full view of the runway, with additional cameras/screens focussing on other hotspots. Therefore, the orientation of the ATCO in relation to the runway will be different than in the current tower and very similar to the other airport. This will contribute to the ATCO confusion in seeing where the aircraft is calling from.
- Traffic monitoring activities (position, track altitude, separation, performance, clearance status) are considered since they determine how likely it is for the ATCO to confuse the two aircraft and give the wrong instructions. This is included in the probability of confusion of ATCO and consequently giving the wrong instruction ($ATCO_F$ (*F* {Message Filter [ATCO]}))

The following are considered to be out of scope:

- Weather, since weather must be good for this simulation to occur.
- Transmission of wrong airport related information. This is another hazard identified in the hazard identification process i.e. Hazard 7: Information pertaining to the wrong airport passed to aircraft and is considered out of scope for this agent-based model.

MASA Identification

To identify all the necessary MASA interactions, an analysis of all agent and non-agent entities is presented below.

The following agents are considered for MASA:

- Aircraft i, where i∈ {Aircraft Cork Departing_k, Aircraft Cork Landing_k, Aircraft Shannon Departing_k)
- Pilot i, with i referring to aircraft i
- Airport j, with j ∈ {Shannon, Cork}
- Communication system j, with j ∈ {Shannon, Cork}
- Remote Tower System

- ATCO

Frequency j, with j∈ {Shannon, Cork}, is an Interaction Petri Net, not a non-agent entity.

Agent and non-agents' relevant own states

This section presents the situation awareness of the agents and non-agents regarding their own state.

Aircraft i

$$\sigma_{aircraft\ i}^{aircraft\ i} = SA\ of\ aircraft\ \ i\ about\ itself\ = \begin{pmatrix} Identity_{aircraft\ i}^{aircraft\ i} \\ State_{airrcraft\ i}^{aircraft\ i} \\ Mode_{aircraft\ i}^{aircraft\ i} \\ Intent_{aircraft\ i}^{aircraft\ i} \end{pmatrix} = \begin{pmatrix} Callsign\ aircraft\ i \\ 2D\ position \\ \{PetriNetplaces\} \end{pmatrix},$$

where {PN Places} = {Flight modes} x {Shannon, Cork}

For aircraft i the intent is not relevant as this is managed by the pilot.

Pilot i

$$\sigma_{Pilot\ i}^{Pilot\ i} = SA\ of\ pilot\ \ i\ about\ itself\ = \begin{pmatrix} Identity_{pilot\ i}^{pilot\ i} \\ State_{pilot\ i}^{pilot\ i} \\ Mode_{pilot\ i}^{pilot\ i} \\ Intent_{pilot\ i}^{pilot\ i} \end{pmatrix} = \begin{pmatrix} Callsign\ aircraft\ i \\ \\ \{Petri\ Net\ Places\} \\ Intent \end{pmatrix},$$

where {PN places} = {P1, P2, P3, P4, P5, P6}

Airport j

$$\sigma_{airport\ j}^{airport\ j} = SA\ of\ airport\ j\ about\ itself\ = \begin{pmatrix} Identity_{aiport\ j}^{airport\ j} \\ State_{airport\ j}^{airport\ j} \\ Mode_{airport\ j}^{airport\ j} \\ Intent_{airport\ j}^{airport\ j} \end{pmatrix} = \begin{pmatrix} airport\ \mathrm{j}\ name \\ Runway/taxiway\ \text{layout} \\ \{Petri\ Net\ Places\} \end{pmatrix}$$

where {PN places} = {Open, Closed}

Communication system j

$$\sigma_{commsyst_j}^{commsyst_j} = SA\ of\ comm\ sys\ j\ about\ itself = \begin{pmatrix} Identity_{commsys\ j}^{commsys\ j} \\ State_{commsys\ j}^{commsys\ j} \\ Mode_{commsys\ j}^{commsys\ j} \\ Intent_{commsys\ j}^{commsys\ j} \end{pmatrix} = \begin{pmatrix} airport\ \mathrm{j}\ name \\ \\ \{PetriNetPlaces\} \end{pmatrix},$$

where {PN places} = {Busy, Not busy}

ATCO

$$\sigma_{ATCO}^{ATCO} = SA\ of\ ATCO\ about\ itself = \begin{pmatrix} Identity_{ATCO}^{ATCO} \\ State_{ATCO}^{ATCO} \\ Mode_{ATCO}^{ATCO} \\ Intent_{ATCO}^{ATCO} \end{pmatrix} = \begin{pmatrix} \{PetriNetPlaces\} \end{pmatrix},$$

Where {PN places} = $\bigotimes_{PN}$ {PN places}

Remote Tower system

$$\sigma_{Remote\ Tower\ system}^{Remote\ Tower\ system} = \begin{pmatrix} Identity_{Remote\ Tower\ system}^{Remote\ Tower\ system} \\ State_{Remote\ Tower\ system}^{Remote\ Tower\ system} \\ Mode_{Remote\ Tower\ system}^{Remote\ Tower\ system} \\ Intent_{Remote\ Tower\ system}^{Remote\ Tower\ system} \end{pmatrix} = \begin{pmatrix} \{PetriNetPlaces\} \end{pmatrix},$$

where {PN places} = {Working, Not working}

Relevant MASA elements per agent

Some agents have MASA about other (non)agents.

The agents that have no SA about any other agent:

- Aircraft i;
- Airport j;
- Comm system j

The agents that have MASA about some other agents:

- Pilot i has MASA about aircraft i, about the corresponding airport, about other aircraft on that airport. Pilot has no SA about ATCO, instead the pilot switches to a particular Petri Net mode upon receiving a clearance from ATCO.
- Remote Tower System has MASA about both airports and all aircraft on these airports.
- ATCO has MASA about Remote Tower System, both airports, and pilots and the aircraft on these airports.

Pilot i MASA

SA of pilot i about aircraft i

This presents the SA of Pilot of $aircraft_i$ of $airport_j$ about his/her aircraft.

$$\sigma_{pilot_i}^{aircraft\ i} = \begin{pmatrix} Identity_{pilot\ i}^{aircraft\ i} \\ State_{pilot\ i}^{aircraft\ i} \\ Mode_{pilot\ i}^{aircraft\ i} \\ Intent_{pilot\ i}^{aircraft\ i} \end{pmatrix} = \begin{pmatrix} Callsign\ aircraft\ i \\ 2D\ position \\ \{Petri\ Net\ Places\} \end{pmatrix},$$

where {PN places} = {Flight modes} x {Shannon, Cork}

The SA of the pilot i of its own aircraft is in scope. The pilot needs to know where his/her aircraft is at any point of the simulation, so as to decide what type of clearance s/he can request. A pilot needs to know its aircraft position for taxiing, etc.

SA of pilot i about aircraft k; i≠k

This represents the SA of $Pilot_i$ of $aircraft_k$ about the other aircraft at the same airport.

$$\sigma_{pilot_i}^{aircraft\ k} = \begin{pmatrix} Identity_{pilot\ i}^{aircraft\ k} \\ State_{pilot\ i}^{aircraft\ k} \\ Mode_{pilot\ i}^{aircraft\ k} \\ Intent_{pilot\ i}^{aircraft\ k} \end{pmatrix} = \begin{pmatrix} \\ \{PetriNetplaces\} \end{pmatrix},$$

if $airport(\sigma_{aircraft\ k}^{aircraft\ k}) = airport(\sigma_{pilot\ i}^{aircraft\ i})$, i≠k

where {PN places} = Flight modes} x {Shannon, Cork}.

SA of pilot i about airport j

$$\sigma_{pilot\ i}^{airport\ j} = \begin{pmatrix} Identity_{pilot\ i}^{airport\ j} \\ State_{pilot\ i}^{airport\ j} \\ Mode_{pilot\ i}^{airport\ j} \\ Intent_{pilot\ i}^{airport\ j} \end{pmatrix} = \begin{pmatrix} airport\ \mathrm{j}\ name \\ \frac{Runway}{taxiway} layout \\ \{PetriNetPlaces\} \end{pmatrix},$$

$$if\ \mathrm{j} = \ \mathrm{airport}\ (\sigma_{pilot\ i}^{aircraft\ i}),$$

where {PN places} = {Open, Closed}

The pilot has to know where s/he is, i.e. what airport, what is the airport runway/taxiway layout.

Remote Tower System MASA

SA of Remote Tower System about aircraft i

$$\sigma_{Remote\ Tower\ System}^{aircraft\ i} = \begin{pmatrix} Identity_{Remote\ Tower\ System}^{aircraft\ i} \\ State_{Remote\ Tower\ System}^{aircraft\ i} \\ Mode_{Remote\ Tower\ System}^{aircraft\ i} \\ Intent_{Remote\ Tower\ System}^{aircraft\ i} \end{pmatrix} = \begin{pmatrix} Callsign\ aircraft\ i \\ 2D\ position \\ \{Petri\ Net\ Places\} \end{pmatrix}$$

Note that the remote tower system is solely replacing ATCO's out of the window view to localize the aircraft positions on the airport surface.

SA of Remote Tower System about airport j

$$\sigma_{Remote\ Tower\ System}^{airport\ j} = \begin{pmatrix} Identity_{Remote\ Tower\ System}^{airport\ j} \\ State_{Remote\ Tower\ System}^{airport\ j} \\ Mode_{Remote\ Tower\ System}^{airport\ j} \\ Intent_{Remote\ Tower\ System}^{airport\ j} \end{pmatrix} = \begin{pmatrix} airport\ \mathrm{j}\ name \\ Runway/taxiway\ \mathrm{layout} \\ \{Petri\ Net\ Places\} \end{pmatrix}$$

ATCO MASA

SA of ATCO about aircraft i

$$\sigma_{ATCO}^{aircraft\ i} = \begin{pmatrix} Identity_{ATCO}^{aircraft\ i} \\ State_{ATCO}^{aircraft\ i} \\ Mode_{ATCO}^{aircraft\ i} \\ Intent_{ATCO}^{aircraft\ i} \end{pmatrix} = \begin{pmatrix} Callsign\ aircraft\ i \\ 2D\ position \\ \{PetriNetplaces\} \end{pmatrix}$$

SA of ATCO about pilot i

The ATCO has to maintain SA for pilots of the Aircraft Cork Landing_k, Aircraft Cork Departing_k and Aircraft Shannon_k.

$$\sigma_{ATCO}^{pilot\ i} = \begin{pmatrix} Identity_{ATCO}^{pilot\ i} \\ State_{ATCO}^{pilot\ i} \\ Mode_{ATCO}^{pilot\ i} \\ Intent_{ATCO}^{pilot\ i} \end{pmatrix} = \begin{pmatrix} Callsign\ aircraft\ i \\ \\ \{PetriNetplaces\} \\ Intent \end{pmatrix}$$

The identity of the aircraft is duplicated from the SA of ATCO about aircraft, same applies to airport(state), which is included in the aircraft SA. The mode includes pilot intention, i.e. pilot request to line up or land, and the intent is the ATCO clearance given to the pilot.

SA of ATCO about airport j

$$\sigma_{ATCO}^{airport\ j} = \begin{pmatrix} Identity_{ATCO}^{airport\ j} \\ State_{ATCO}^{airport\ j} \\ Mode_{ATCO}^{airport\ j} \\ Intent_{ATCO}^{airport\ j} \end{pmatrix} = \begin{pmatrix} airport\ \text{j}\ name \\ Runway/taxiway\ \text{layout} \\ \{PetriNetPlaces\} \end{pmatrix}$$

SA of ATCO about Remote Tower System

This presents the ATCO SA about the Remote Tower system.

$$\sigma_{ATCO}^{Remote\ Tower\ System} = \begin{pmatrix} Identity_{ATCO}^{Remote\ Tower\ System} \\ State_{ATCO}^{Remote\ Tower\ System} \\ Mode_{ATCO}^{Remote\ Tower\ System} \\ Intent_{ATCO}^{Remote\ Tower\ System} \end{pmatrix} = \begin{pmatrix} \{PetriNetPlaces\} \end{pmatrix}$$

7. Simulation Code Development

The agent-based model of the Multiple Remote Tower operations will be simulated in MATLAB. This chapter describes the petri net model, followed by the MATLAB implementation strategy and the presentation of the verification process of the Petri Net model of Multiple Remote Tower.

7.1 Multi agent Model of Multiple Remote Tower operation Petri Net Specifications

This section provides an overview of the agent-based model for multiple remote tower and the assumptions on which the model is based on.

Chapter 6 presents what is in scope for the petri net model and was the input for developing the petri net model.

Details on the Petri Net Model are presented in Appendix E of the MSc. Thesis.

A graphical presentation of the Petri Net Model for Multiple Remote Tower is presented in Figure 7-1.

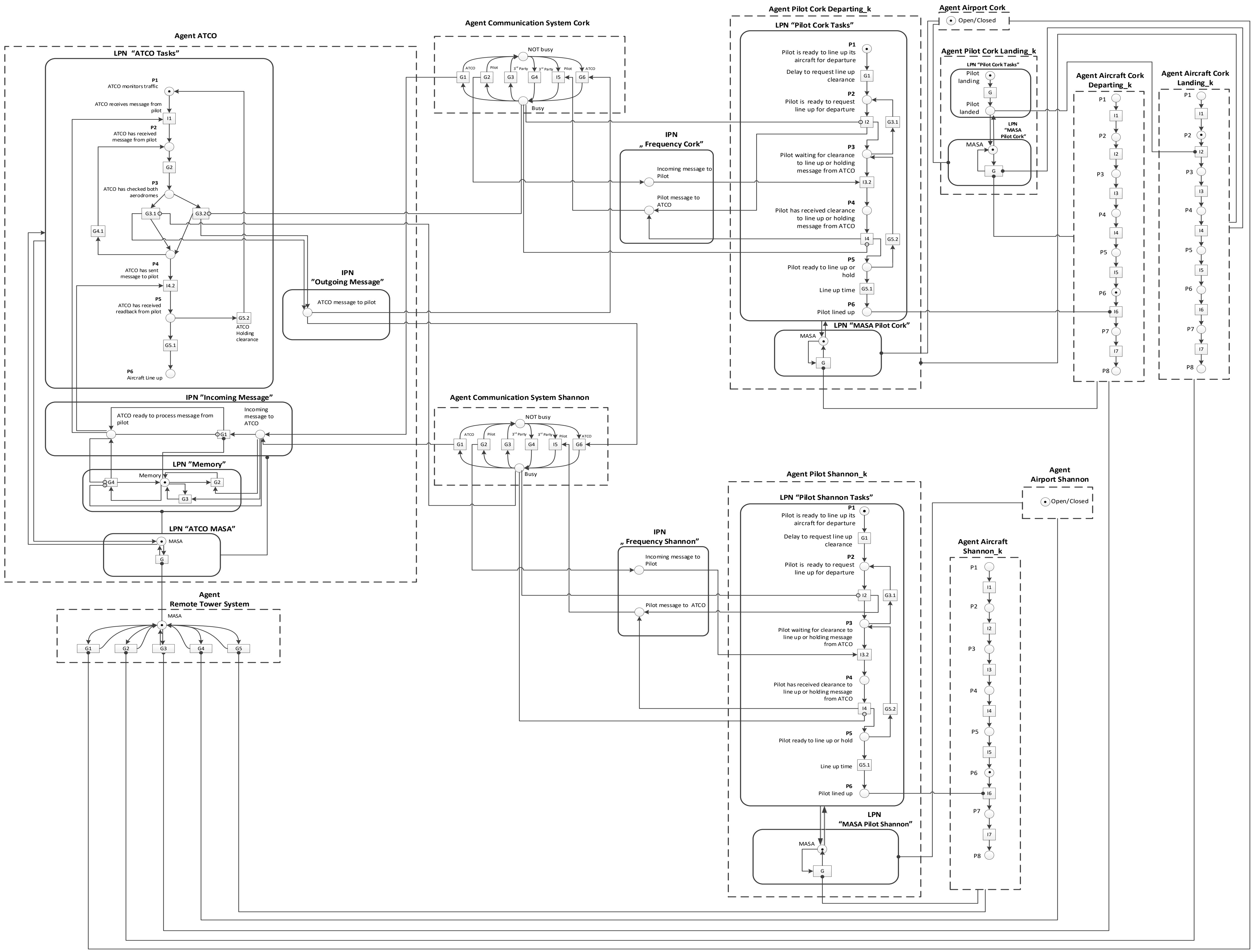


Figure 7-1: Petri Net Model for Multiple Remote Tower

In total there are 12 agents and 2 Interconnecting Petri Nets, with their associated Local Petri Nets (LPN) and interconnecting Petri Nets (IPN) and as presented below.

Agents

ATCO

- LPNs
  - ATCO MASA
    LPN "ATCO MASA" filters the messages for the ATCO, i.e. open to all aircraft or waiting for readback, and therefore not able to take in another message. It also contains information about the aircraft (callsign and location on the airport), pilots (callsign and intent) and ATC clearance.
  - ATCO Tasks
    LPN "ATCO Tasks" summarises the actions that the ATCO performs when an ATCO receives a request from a pilot.
  - Memory
    LPN" Memory" acts as the ATCO memory, storing messages for the ATCO that the ATCO cannot answer when s/he is busy managing other requests.
- IPNs
  - Incoming Message
    The IPN "Incoming Message" handles the all the incoming messages to ATCO.
  - Outgoing Message
    The IPN "Outgoing Message" handles all the messages that the ATCO transmits to the pilots.

Pilots

Pilot Cork Landing_k

- LPN" MASA Pilot Cork"
  The place MASA represents the situation awareness of the pilot and contains SA of Pilot Cork Landing_k about Aircraft Cork Landing_k, the SA of Pilot Cork Landing_k about Aircraft Cork Departing_k, SA of Pilot Cork Landing_k about Airport Cork and SA of Pilot Cork Departing_k about ATCO.
- LPN "Pilot Cork Tasks"
  Agent Pilot Cork Landing_k represents the Cork pilot landing at the airport.

Pilot Cork Departing_k

- LPN" MASA Pilot Cork"
  The LPN "MASA" The place MASA represents the situation awareness of the pilot and contains the SA of Pilot Cork Departing_k about Aircraft Cork Departing_k, SA of Pilot Cork Departing_k about Aircraft Cork Landing_k, SA of Pilot Cork Departing_k about Airport Cork and SA of Pilot Cork Departing_k about ATCO.
- LPN "Pilot Cork Tasks"

Agent Pilot Cork Departing_k represents the Cork pilot waiting for line up clearance at the runway departure holding point and the actions of the pilot to line up.

Pilot Shannon_k

- LPN" MASA Pilot Shannon"
  The LPN "MASA" represents the situation awareness of the pilot and contains the SA of Pilot Shannon Departing_k about Aircraft Shannon Departing_k, and SA of Pilot Shannon Departing_k about airport Shannon.
- LPN "Pilot Shannon Tasks"
  Agent Pilot Shannon Departing_k represents the Shannon pilot waiting for line up clearance at the runway departure holding point and the actions of the pilot to line up.

Aircraft

Aircraft Cork Landing_k

Agent Aircraft Cork Landing_k has been designed to recreate aircraft landing in Cork.

Aircraft Cork Departing_k

Agent Aircraft Cork Departing_k has been designed to recreate aircraft departing in Cork.

Aircraft Shannon_k

Agent Aircraft Shannon_k has been designed to recreate aircraft departing in Shannon.

Airports

Airport Cork

Agent Airport Cork represents the Cork airport. In this scenario, the airport is open.

Airport Shannon

Agent Airport Shannon represents the Shannon airport. In this scenario, the airport is open.

Communication System

Communication System Cork

Agent Communication System Cork has been designed to recreate the frequency in Cork Airport.

Communication System Shannon

Agent Communication System Shannon has been designed to recreate the frequency in Shannon Airport.

Remote Tower System

Agent Remote Tower system replicated the remote tower screens in the remote tower modules and recreates what the ATCO sees outside. It acts like an extended mind for the ATCO.

IPNs

Frequency Cork

This IPN is used to link the two agents: “Pilot Cork Departing_k” and “Communication System Cork”.

Frequency Shannon

This IPN is used to link the two agents: “Pilot Shannon_k” and “Communication System Shannon”.

7.2 Implementation strategy

The specified Petri Net model has been implemented in MATLAB using the following strategy:

- The first step was to programme transitions and all places for all LPNs, IPNs followed by the petri net process of agents with multiple LPNs, and finally the main Petri Net process running the complete simulation.
- In the program the places are programmed as variables (matrices) and the transitions are programmed as MATLAB functions.
- The Petri Net process of all agents is programmed as the script file called Main.m, which calls the routines.
- The execution of transitions is programmed in separate script files as routines. There is a routine for each LPN.

7.3 Simulation Assumptions

The assumptions and choices for the agent-based model are presented in Chapter 4 and Appendix E. The following section sets the assumptions considered for the simulation.

General simulation assumptions

- ATCO being ready to receive communications from pilot, i.e. ATCO is free and monitors traffic.
- Aircraft Cork Landing_k has landing clearance and therefore there is a potential for conflict in Cork.
- Aircraft Shannon_k and Aircraft Cork Departing_k are both at the Departure Holding Points in airport Shannon and Airport Cork. Who is calling first is determined by the delay t_G (Time delay to request line up clearance from ATCO).
- If Pilot Cork Departing_k questions the ATCO for the incorrect callsign or instruction the simulation will end since it is assumed that the ATCO will realize the mistake when pilot questions him/her.

Agents specific assumptions

- **ATCO**
  Initial MASA is correct.

- **Pilot Cork Landing_k**
  Initially, Pilot Landing_k has landing clearance.

  Initial MASA is correct.

- **Pilot Cork Departing_k**
  Initial MASA is correct.

- **Pilot Shannon_k**
  Initial MASA is correct.

- **Aircraft Cork Landing_k**
  The aircraft can be in 8 places, i.e. Approach, Landing, Taxi in, Gate, Taxi out, Departure Holding Point. The scope of this simulation includes only the status change of agent Aircraft Cork Landing_k from place Landing to place Taxi in.

  2D Position of aircraft is not needed to be modelled in this scenario, as landing position is fixed.

  Aircraft Cork Landing_k will be modelled as the duration of the simulation. Simulation will end when aircraft lands.

- **Aircraft Cork Departing_k**
  The aircraft can be in 8 places, i.e. Approach, Landing, Taxi in, Gate, Taxi out, Departure Holding Point. The scope of this simulation includes only the status change of agent from place Departure Holding Point to place Line up.

  2D Position of aircraft is not needed to be modelled in this scenario, as departing position is fixed.

- **Aircraft Shannon_k**
  The aircraft can be in 8 places, i.e. Approach, Landing, Taxi in, Gate, Taxi out, Departure Holding Point. The scope of this simulation includes only the status change of agent from place Departure Holding Point to place Line up.

  2D Position of aircraft is not needed to be modelled in this scenario, as departing position is fixed.

- **Airport Cork**
  Airport is open.

  Name $_{\text{Airport\_Cork:}}$ This is the name of the airport where the aircraft is located. This is not going to be modelled in the petri net model.

  Runway/taxiway layout $_{\text{Airport\_Cork:}}$ This is not modelled in the petri net model.

- **Airport Shannon**
  Airport is open.

  Name $_{Airport\_Shannon}$: This is the name of the airport where the aircraft is located. This is not going to be modelled in the petri net model.

  Runway/taxiway layout $_{Airport\_Shannon}$: This is not modelled in the petri net model.

- **Communication System Cork**
  None

- **Communication System Shannon**
  None

- **Remote Tower System**
  The remote tower system is not in the simulation, as it is only a means of presenting the information to the ATCO (extended memory), and all the information from the remote tower system is passed to and duplicated in the ATCO MASA.

- **Frequency Cork**
  None

- **Frequency Shannon**
  None

7.4 MATLAB Code Verification Strategy

The MATLAB program was tested using the following testing strategy:

Item Verified	Verification Strategy
All program	If an error is found and corrected, the verification process is restarted, and all items are verified again.
Variables	Ensure all places are captured in variables. Ensure all the variables captured correctly.
Functions	Ensure the functions perform as expected by inputting different input parameters and checking whether the output is as expected. Ensure each step of a function is working by assessing each calculation step individually.
Complete petri net model	Ensure the model performs as expected by assessing different inputs with the expected and actual output at each timestep of the simulation.

8. MC Simulation Results

This chapter details the MC scenario being simulated, the MC simulation results overview and analysis. This represents Step 5 of Figure 1-2.

8.1 MC scenario being simulated

This section presents the scenario modelled in the MC simulation. Further details on how this scenario was constructed can be found in Chapter 5.

A graphical presentation of the initial scenario setting is provided in Figure 8-1 below.

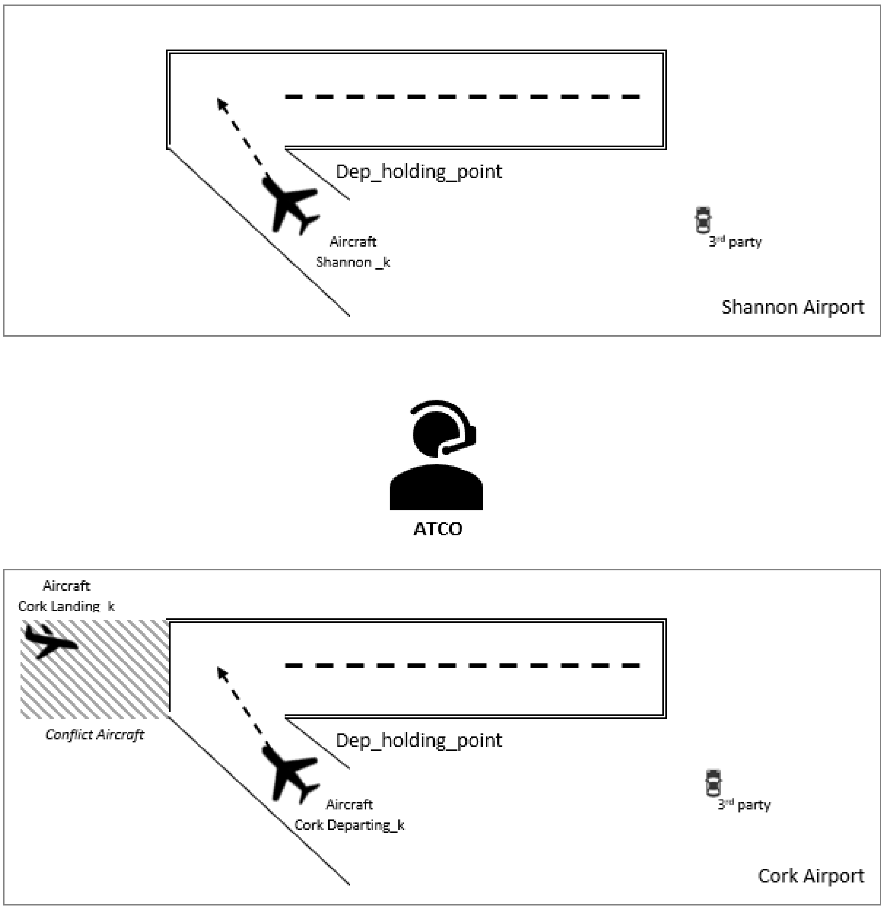


Figure 8-1: Multiple Remote Tower Scenario Diagram

The scenario involves three aircraft, one in Shannon airport and two in Cork airport. In Shannon there is one aircraft at Departure Holding Point (Aircraft Shannon_k). In Cork, there is one aircraft at Departure Holding Point (Aircraft Cork Departing_k), and another aircraft on final approach (Aircraft Cork Landing_k), which is already cleared to land by the ATCO. The initial position of the aircraft landing is from uniform distribution along the final approach path from 3 minutes (earliest the ATCO can give the landing clearance) until the 30 seconds before landing (the latest the ATCO gives the landing clearance, i.e. at decision height).

In terms of callsign similarity, callsigns of Aircraft Shannon_k, Aircraft Cork Departing_k and Aircraft Cork Landing_k are totally different from each other. Also, all pilots in the simulation are experienced pilots.

Other traffic (vehicles in Shannon or Cork) is captured by the parameter $t_{commsystem3rdpartyfree}$. This variable describes the duration of communication systems being free from 3rd party communication.

The ATCO is monitoring traffic and is ready to communicate with any aircraft from both Shannon and Cork.

There are no MASA differences as initial condition for either the ATCO or the pilots.

Both communication systems in Shannon and Cork are free for communication.

Table 8-1 presents the parameter values adopted for the agent-based model. Note this table has been developed at the end of Appendix E.

Table 8-1: Parameter values used for the simulated scenario

Agent	Parameter	Description	Estimation/Initial values
Pilot Cork Departing	$t_{G1} \in \mathbb{R}$	Pilot time delay to request line up clearance from ATCO.	Sample ≥ 0 from Gaussian distribution with: Mean=5 s Std Dev=1 s
	$PILOT_{aid} \in \mathbb{R}$	Initial callsign of aircraft and known to pilot.	Callsign set for all MC simulation runs as totally different to the one for Aircraft Shannon_k.
	$P(PILOT_{student}) \in \mathbb{R}$	Probability that the pilot is a student or experienced.	The MC simulation is only considering the experienced pilots. $P(PILOT_{student})=0$
	$t_{RRG3} \in \mathbb{R}$	Time to repeat request by pilot.	If fired by I2: Sample ≥ 0 from Gaussian distribution with:

			Mean=30 s Std Dev=5 s If fired by G5.2: Sample ≥ 0 from Gaussian distribution with: Mean=60 s Std Dev=5 s
	$t_{G5.1} \in \mathbb{R}$	Time it takes the aircraft to start and enter the runway from the moment of receiving clearance.	Sample ≥ 0 from Gaussian distribution with: Mean=3 s Std Dev=1 s
	P (Callsign confusion by pilot|callsigns are very similar) $\in \mathbb{R}$ P (Callsign confusion by pilot|callsigns are similar) $\in \mathbb{R}$ P (Callsign confusion by pilot|callsigns are totally different$\in \mathbb{R}$	Conditional probability of callsign confusion by pilot given callsigns are very similar, similar or totally different.	If callsigns of the aircraft are: - P (Callsign confusion by pilot|callsigns are very similar): 1 in 300 *(hard coded value)* - P (Callsign confusion by pilot|callsigns are similar): 1 in 500 *(hard coded value)* - P (Callsign confusion by pilot|callsigns are totally different: 1 in 5000 *(hard coded value)*
Pilot Shannon_k	$t_{G1} \in \mathbb{R}$	Pilot time delay to request line up clearance from ATCO.	Sample ≥ 0 from Gaussian distribution with:

			Mean=5 s Std Dev=1 s
	$PILOT_{aid} \in \mathbb{R}$	Initial callsign of aircraft and known to pilot.	Callsign set for all MC simulation runs as totally different to the one for aircraft Cork Departing_k.
	P ($PILOT_{student}$) $\in \mathbb{R}$	Probability that the pilot is a student or experienced.	The MC simulation is only considering the experienced pilots. P ($PILOT_{student}$)=0
	$t_{RRG3} \in \mathbb{R}$	Time to repeat request by pilot.	If fired by I2: Sample ≥ 0 from Gaussian distribution with: Mean=30 s Std Dev=5 s If fired by G5.2: Sample ≥ 0 from Gaussian distribution with: Mean=60 s Std Dev=5 s
	$t_{G5.1} \in \mathbb{R}$	Time it takes the aircraft to start and enter the runway from the moment of receiving clearance.	Sample ≥ 0 from Gaussian distribution with: Mean=3 s Std Dev=1 s
	P (Callsign confusion by pilot|callsigns	Conditional probability of callsign confusion by pilot given callsigns are	If callsigns of the aircraft are:

	are very similar) $\in \mathbb{R}$ P (Callsign confusion by pilot|callsigns are similar) $\in \mathbb{R}$ P (Callsign confusion by pilot|callsigns are totally different$\in \mathbb{R}$	very similar, similar or totally different.	- P (Callsign confusion by pilot|callsigns are very similar): 1 in 300 *(hard coded value)* - P (Callsign confusion by pilot|callsigns are similar): 1 in 500 *(hard coded value)* - P (Callsign confusion by pilot|callsigns are totally different: 1 in 5000 *(hard coded value)*
Agent Communication System Cork	$t_{commsystem3rdpartyfree} \in \mathbb{R}$	Duration of communication system being free from 3rd party communication. When $t_{commsystem3rdpartyfree} \leq 0$, a 3rd party communication occurs on the communication system.	Sample ≥ 0 from Gaussian distribution with: Mean=30 s Std Dev=10 s
	$t_{commsystemoccup} \in \mathbb{R}$	Duration of the transmission of communication system.	Sample ≥ 0 from Gaussian distribution with: Mean= 5 s Std Dev=2 s
Agent Communication System Shannon	$t_{commsystem3rdpartyfree} \in \mathbb{R}$	Duration of communication system being free from 3rd party communication. When $t_{commsystem3rdpartyfree} \leq 0$, a 3rd party	Sample ≥ 0 from Gaussian distribution with: Mean=30 s Std Dev=10 s

		communication occurs on the communication system.	
	$t_{commsystemoccup} \in \mathbb{R}$	Duration of the transmission of communication system.	Sample ≥ 0 from Gaussian distribution with: Mean= 5 s Std Dev=2 s
Agent ATCO	$t_{checkaerodromes} \in \mathbb{R}$	Time to check both aerodromes and deciding on course of action for aircraft.	Uniform distribution between 2 and 7 seconds.
	$t_{recheck} \in \mathbb{R}$	If no readback is received from the pilot, the ATCO will recheck the aerodromes to see what happened. This duration of the rechecking is $t_{recheck}$.	Uniform distribution between 20 and 30 seconds.
	P (wrong frequency) $\in \mathbb{R}$	Probability of selection of wrong frequency for ATCO.	Probability of ATCO selection of wrong frequency is estimated: 1 in 5000 *(hard coded value)*
	P (Callsign confusion by ATCO|callsigns are very similar) $\in \mathbb{R}$ P (Callsign confusion by ATCO|callsigns are similar) $\in \mathbb{R}$	Conditional probability of callsign confusion by ATCO given callsigns are very similar, similar or totally different.	If callsigns of the aircraft are: - P (Callsign confusion by ATCO|callsigns are very similar): 1 in 300 *(hard coded value)* - P (Callsign confusion by ATCO|callsigns are similar): 1 in 500 *(hard coded value)* - P (Callsign confusion by ATCO|callsigns are

	P (Callsign confusion by ATCO|callsigns are totally different) ∈ ℝ		totally different: 1 in 5000 *(hard coded value)*
	P (ATCO forgets about the aircraft landing) ∈ ℝ	Probability of ATCO forgetting about the aircraft landing.	Probability of ATCO forgetting about the aircraft landing: 1 in 5000 *(hard coded value)*
	P (ATCO wrong message|ATCO forgets about the aircraft landing) ∈ ℝ	Conditional probability of ATCO message to Pilot Cork Departing is wrong given the ATCO forgets about the aircraft landing.	Probabilities of wrong instruction due to ATCO forgetting about the landing aircraft: 100% *(hard coded value)* *If the ATCO forgets about the landing aircraft, then the ATCO thinks the runway is free and therefore clears aircraft Cork Departing_k to line up.*

A MC simulation run ends if one of the following three occurs:

- Aircraft in Cork on final approach has landed.
- Aircraft in Cork at Departure Holding Point has lined up.
- Pilot of aircraft at Departure Holding Point in Cork or Shannon airport has questioned the ATCO.
  The pilot can question the callsign (in the case of ATCO callsign confusion) or the instruction (in the case the pilot is told to line up). In this situation, the assumption is the ATCO will either reassess the instruction and correct it or the pilot would be reluctant to follow the instruction, none of which would result in a runway incursion.

For each simulation run, the following results are collected:

1. Runway incursions[3]:
   - For Cork, the runway incursions occur when the pilot enters the runway (runway incursion with authorised presence).
   - For Shannon, the runway incisions occur when the pilot Shannon enters the runway following a wrong ATCO clearance (wrong callsign or wrong instruction).
2. Other non-nominal events which do not result in a runway incursion:
   - Number of ATCO callsign confusions for Pilot Cork Departing_k. This occurs when ATCO confuses the callsign for the Pilot Cork Departing_k.
   - Number of ATCO callsign confusions for Pilot Shannon. This occurs when ATCO confuses the callsign for the Pilot Shannon.
   - Number of ATCO selection of wrong frequency for Cork. This occurs when the ATCO wants to select Cork but selects Shannon.
   - Number of ATCO selection of wrong frequency for Shannon. This occurs when ATCO wants to select Shannon but selects Cork.
   - Number of times ATCO forgets about the aircraft landing in Cork.
   - Number of Pilot Cork Departing_k callsign confusion when wrong callsign is received. This occurs when the Pilot Cork Departing_k does not identify that the message from the ATCO (callsign used) is not for him/her.
   - Number of Pilot Shannon_k callsign confusion when wrong callsign is received. This occurs when the Pilot Shannon_k does not identify that the message from the ATCO (callsign used) is not for him/her.
   - Number of times Pilot Cork Departing_k questions the ATCO. This occurs when Pilot Cork Departing_k questions the ATCO when the message received is wrong.
   - Number of times Pilot Shannon_k questions the ATCO. This occurs when the Pilot Shannon_k does not identify that the message from the ATCO (callsign used) is not for him/her.

---

[3]*" Any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle or person on the protected area of a surface designated for the landing and take-off of aircraft."* (ICAO, 2016)

8.2 MC simulation results overview

The MC simulation contains 1,000,000 simulation runs.

The simulation results distinguish between runway incursions and other non-nominal events.

The high-level simulation results show that in 998,841 out of 1,000,000 simulation runs no non-nominal event occurs (approximately 99.88%). In the remaining 1,159 simulation runs a runway incursion or other non-nominal events occur (approximately 0.12%).

Of the 1,159 simulation runs, 45 runs (approximately 0.005% of total number of runs) result in a runway incursion at Cork airport, and 1,114 runs (approximately 0.111% of total number of runs) are other non-nominal events.

Next, the 1,159 simulation runs are analysed.

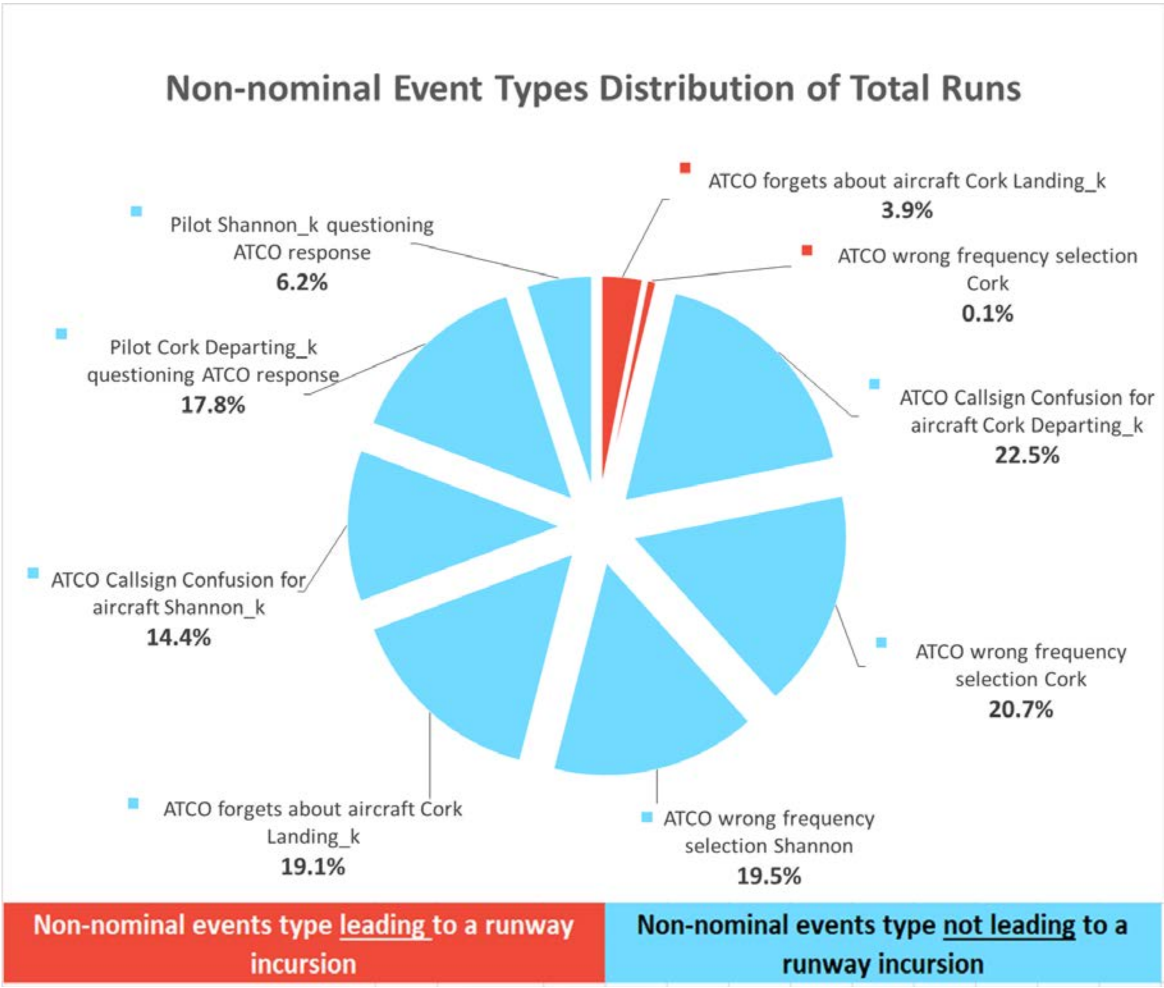


Figure 8-2: MC Simulation Results – Distribution of non-nominal event types

Figure 8-2 above presents the number of non-nominal events as a percentage of simulation runs, i.e. 22.5 % of the 1,159 MC runs contain ATCO Callsign Confusion for aircraft Cork Departing_k. Due to the fact that one run can have one or more non-nominal events, the percentage from the chart above does not add to 100%.

In summary, the 1,159 MC simulation runs contain:

- Non-nominal events that result in a Runway Incursion:
    - ATCO forgets about aircraft Cork Landing_k: 3.9%
    - ATCO wrong frequency selection Cork: 0.1%
- Other non-nominal events:
    - ATCO non-nominal events:
        - ATCO Callsign Confusion for aircraft Cork Departing_k: 22.5%
        - ATCO wrong frequency selection Cork: 20.7%
        - ATCO wrong frequency selection Shannon: 19.5%
        - ATCO forgets about aircraft Cork Landing_k: 19.1%
        - ATCO Callsign Confusion for aircraft Shannon_k: 14.4%
    - Pilot non-nominal events:
        - Pilot Cork Departing_k questioning ATCO response: 17.8%
        - Pilot Shannon_k questioning ATCO response: 6.2%

To understand why these non-nominal events lead to runway incursions, the simulation runs are analysed in detail below.

8.3 Analysis of simulation runs which lead to a runway incursion

As presented in the section 8.2, there are 45 simulation runs where a runway incursion is observed.

All simulation runs resulting in runway a runway incursion contain the non-nominal event that the ATCO forgets about the aircraft landing in Cork, while one simulation run has in addition the non-nominal event that s/he selects Cork frequency instead of Shannon.

In 44 of 45 runs (97.78%), the Pilot Cork Departing_k requests a line up clearance. The ATCO forgets about the pilot Cork Landing_k and gives a line up clearance.

In one of the 45 runs (2.22%), two non-nominal events occur (ATCO forgets about aircraft Cork Landing_k and ATCO wrong frequency selection Cork), i.e. simulation run 302,914.

The run starts with the Pilot Shannon_k requesting line up (ATCO Tasks Transition I1). ATCO gives Pilot Shannon_k line up clearance (ATCO Tasks Transition G3.1), then Pilot Shannon_k confirms the line-up (ATCO Tasks Transition I4.2).

After a couple of seconds, the ATCO wants to clear the pilot Cork Departing_k to line up, which will result in a runway incursion. This is because the ATCO forgets about the landing aircraft in Cork. However, the ATCO does a second mistake, which is to transmit the line-up clearance for the Cork pilot wrongly on the Shannon frequency (ATCO Tasks Transition G3.1 again). Because the pilot in Shannon is already lined up and s/he hears a line up message for a different aircraft, the pilot is ignoring the message and does not alert the ATCO about the mistake. In the meantime, the pilot Cork Departing_k still did not receive a clearance, s/he asks again, and the ATCO repeats his/her previous message (landing clearance), but this time on the correct Cork frequency (ATCO Tasks Transition G3.2). This results in the pilot in Cork lining up and a runway incursion occurring.

This is the worst runway incursion, as it can be seen in the Table 8-2 below, it occurs at 0 seconds from touchdown of aircraft Cork Landing_k, with the pilot starting to line up approximately 3 seconds before. Therefore, in this run a collision could very likely occur and only be avoided if the lining up pilot sees the landing aircraft and does not initiate the line-up.

Therefore, it can be said that in all cases the reason for the runway incursion is that the ATCO forgets about the landing aircraft, and even mistakenly selecting the wrong frequency once does not result in the recovery in the situation awareness difference.

Next, a closer look is taken at the remaining time to land of pilot Cork Landing_k when the runway incursions occur.

Table 8-2 presents the simulation runs which result in a runway incursion, the non-nominal events included, and their respective remaining time to land for the Pilot Cork Landing_k.

Table 8-2: MC Simulation Results- Simulation runs with Runway Incursions and Remaining Time to land and non-nominal events per run

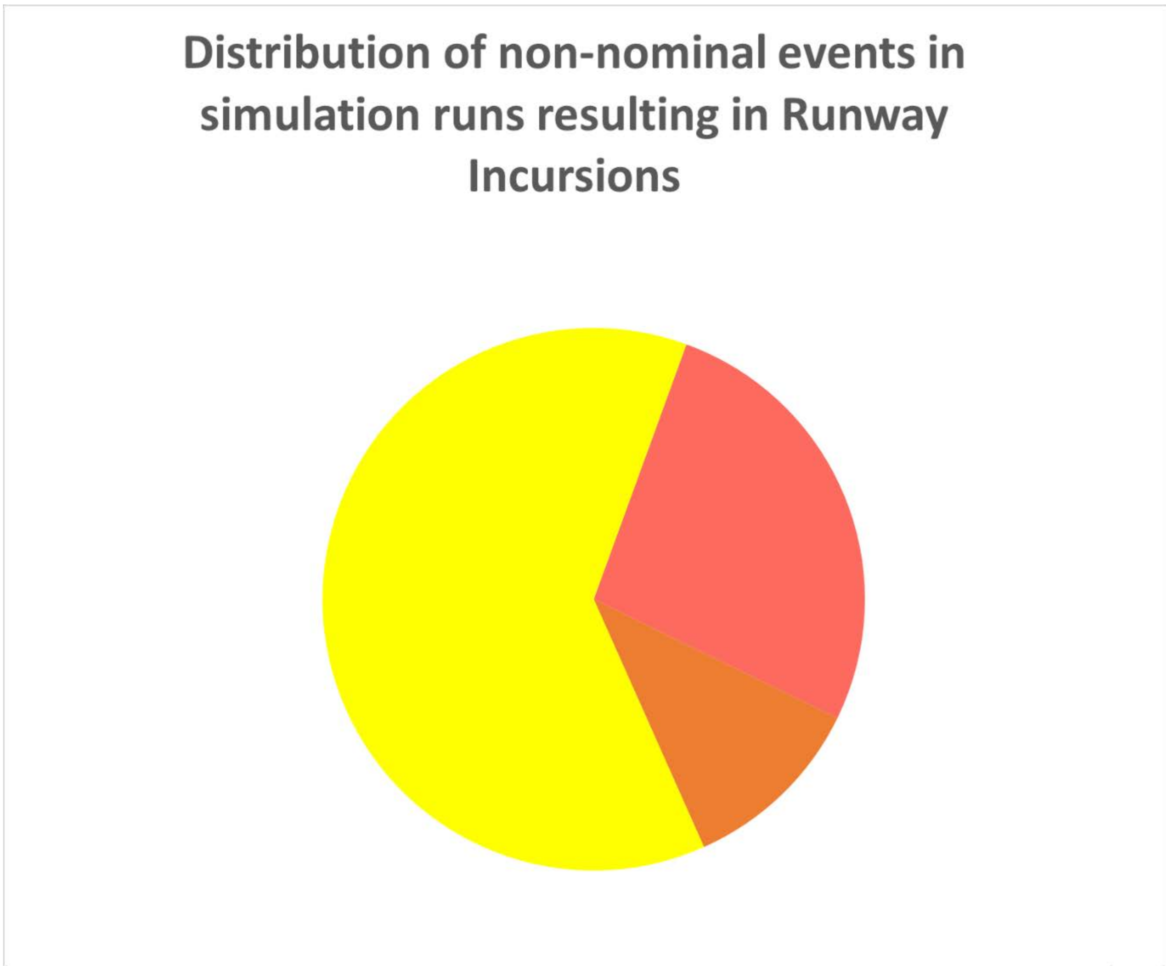
	Simulation No.	Non-nominal event associated with the runway incursion	Remaining time to land for pilot Cork Landing_k (s)
Runway Incursion 1	23,468	ATCO forgets about aircraft Cork Landing_k	107.6
Runway Incursion 2	63,606	ATCO forgets about aircraft Cork Landing_k	154.9
Runway Incursion 3	84,456	ATCO forgets about aircraft Cork Landing_k	86.7
Runway Incursion 4	119,393	ATCO forgets about aircraft Cork Landing_k	36.5
Runway Incursion 5	186,786	ATCO forgets about aircraft Cork Landing_k	96.2

Runway Incursion 6	227,436	ATCO forgets about aircraft Cork Landing_k	8.9
Runway Incursion 7	253,285	ATCO forgets about aircraft Cork Landing_k	101.5
Runway Incursion 8	296,784	ATCO forgets about aircraft Cork Landing_k	3.5
Runway Incursion 9	300,090	ATCO forgets about aircraft Cork Landing_k	54.9
Runway Incursion 10	302,914	ATCO forgets about aircraft Cork Landing_k; ATCO wrong frequency selection Cork	0.0
Runway Incursion 11	323,576	ATCO forgets about aircraft Cork Landing_k	59.7
Runway Incursion 12	326,291	ATCO forgets about aircraft Cork Landing_k	52.2
Runway Incursion 13	346,639	ATCO forgets about aircraft Cork Landing_k	13.9
Runway Incursion 14	358,222	ATCO forgets about aircraft Cork Landing_k	1.9
Runway Incursion 15	421,818	ATCO forgets about aircraft Cork Landing_k	4.7
Runway Incursion 16	427,037	ATCO forgets about aircraft Cork Landing_k	16.1
Runway Incursion 17	441,987	ATCO forgets about aircraft Cork Landing_k	44.2
Runway Incursion 18	443,539	ATCO forgets about aircraft Cork Landing_k	53.8
Runway Incursion 19	475,758	ATCO forgets about aircraft Cork Landing_k	16.2
Runway Incursion 20	491,922	ATCO forgets about aircraft Cork Landing_k	68.0

Runway Incursion 21	527,625	ATCO forgets about aircraft Cork Landing_k	26.1
Runway Incursion 22	529,286	ATCO forgets about aircraft Cork Landing_k	127.5
Runway Incursion 23	571,518	ATCO forgets about aircraft Cork Landing_k	94.2
Runway Incursion 24	576,223	ATCO forgets about aircraft Cork Landing_k	90.0
Runway Incursion 25	577,025	ATCO forgets about aircraft Cork Landing_k	38.6
Runway Incursion 26	593,252	ATCO forgets about aircraft Cork Landing_k	76.7
Runway Incursion 27	601,392	ATCO forgets about aircraft Cork Landing_k	20.1
Runway Incursion 28	617,041	ATCO forgets about aircraft Cork Landing_k	107.7
Runway Incursion 29	659,465	ATCO forgets about aircraft Cork Landing_k	144.7
Runway Incursion 30	662,200	ATCO forgets about aircraft Cork Landing_k	65.2
Runway Incursion 31	672,241	ATCO forgets about aircraft Cork Landing_k	87.2
Runway Incursion 32	682,071	ATCO forgets about aircraft Cork Landing_k	51.8
Runway Incursion 33	708,776	ATCO forgets about aircraft Cork Landing_k	4.9
Runway Incursion 34	737,386	ATCO forgets about aircraft Cork Landing_k	40.8
Runway Incursion 35	739,564	ATCO forgets about aircraft Cork Landing_k	48.3
Runway Incursion 36	753,909	ATCO forgets about aircraft Cork Landing_k	42.3

Runway Incursion 37	774,152	ATCO forgets about aircraft Cork Landing_k	35.8
Runway Incursion 38	784,471	ATCO forgets about aircraft Cork Landing_k	42.0
Runway Incursion 39	826,207	ATCO forgets about aircraft Cork Landing_k	104.4
Runway Incursion 40	840,206	ATCO forgets about aircraft Cork Landing_k	80.2
Runway Incursion 41	856,786	ATCO forgets about aircraft Cork Landing_k	18.2
Runway Incursion 42	882,084	ATCO forgets about aircraft Cork Landing_k	145.8
Runway Incursion 43	888,429	ATCO forgets about aircraft Cork Landing_k	64.0
Runway Incursion 44	932,697	ATCO forgets about aircraft Cork Landing_k	13.6
Runway Incursion 45	975,873	ATCO forgets about aircraft Cork Landing_k	13.8

The categorisation of runway incursions based on the pilot Cork Landing_k remaining time to land is shown in Figure 8-3 below.



a1. Runway incursions occurring when aircraft Cork Landing_k is **less than 20 seconds from landing**	**12**
a2. Runway Incursions occuring when aircraft Cork Landing_k is **at or more than 20 seconds but less than 40 seconds from landing**	**5**
b. Runway incursions occurring when aircraft Cork Landing_kis **at or more than 40 seconds from landing**	**28**

Figure 8-3: MC Simulation Results – Distribution of non-nominal events in simulation runs resulting in runway incursions in Cork

Based on air traffic control subject matter expertise, as described in Chapter 11, the cut-off time to initiate a go-around is 30 seconds.

Figure 8-3 above presents the remaining time to land for the pilot in Cork breakdown based on the view of pilot Cork Landing_k only:

a. Runway incursions that could result in a runway collision: 17

a(1). Runway incursions occurring when aircraft Cork Landing_k is less than 20 seconds from landing: 12

For these runway incursions there is no time to allow any avoiding action by pilot Cork Landing_k to be taken to prevent a collision.

a(2). Runway Incursions occurring when aircraft Cork Landing_k is at or more than 20 seconds but less than 40 seconds from landing: 5

For these runway incursions the pilot Cork Landing_k might have some time to take some type of avoiding action. While there is still potential of an accident, it might not be a collision (i.e. the landing aircraft will try and avoid straight collision and crash land next to the runway).

b. Runway incursions occurring when aircraft Cork Landing_k is at or more than 40 seconds from landing: 28

For these runway incursions, the probability of runway collision is extremely low.

These runway incursions occur when the pilot Cork Landing_k is more than 40 seconds from landing which gives enough time to initiate avoiding action for pilot Cork Landing_k.

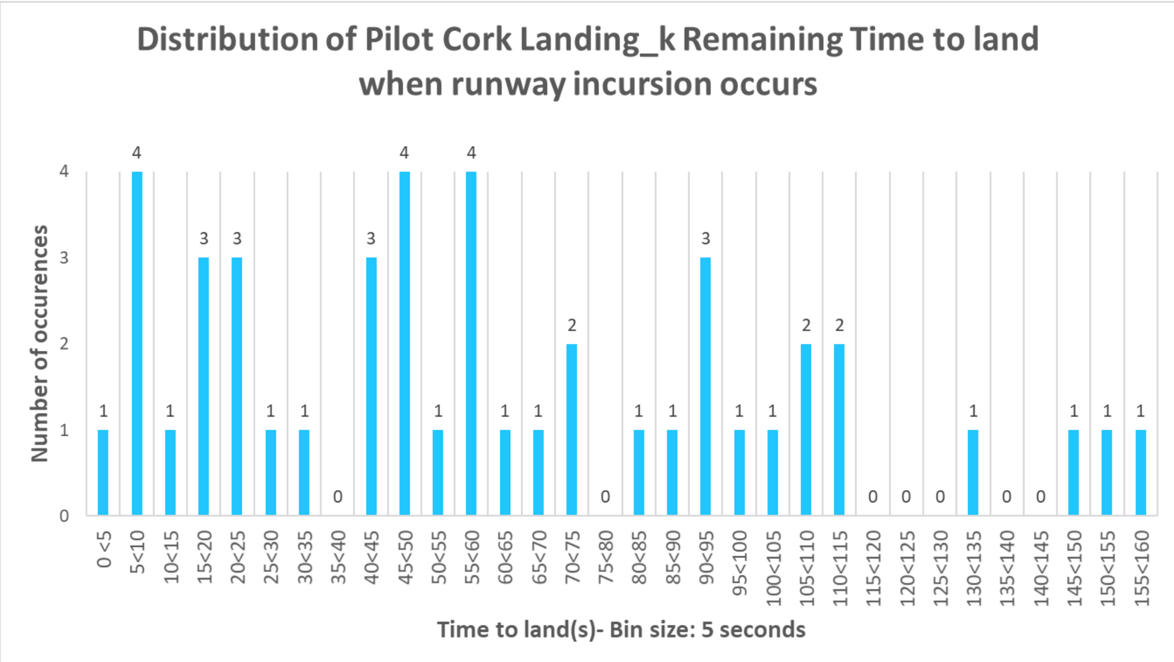


Figure 8-4: MC Results- Distribution of Pilot Cork Landing_k Remaining Time to land when runway incursion occurs

Figure 8-4 above visualises the distribution of the remaining time to land identified in Table 8-2 above. It can be seen that most of the runway incursions happen between 0 and 115 seconds, however a clear pattern is not visible.

Next, the MC simulation runs that do not result in a Runway Incursion are analysed in detail.

8.4 Analysis of simulation runs with non-nominal events which do not lead to a runway incursion

As presented in the section above, there are 1,114 simulation runs where non-nominal events occur, but no runway incursion is observed.

The total number of non-nominal events and their distribution of the total number of non-nominal events are presented in Table 8-3 below.

The 45 runway incursions are not counted in this table, although they fall under types d and f.

Table 8-3: MC Simulation Results- Summary of non-nominal events

Non-nominal events not leading to a runway incursion		
Type	**Total number in MC runs**	**% of the Number of Runs**
c. ATCO Callsign Confusion for aircraft Cork Departing_k	261	22.5%
d. ATCO wrong frequency selection Cork	240	20.7%
e. ATCO wrong frequency selection Shannon	226	19.5%
f. ATCO forgets about aircraft Cork Landing_k	221	19.1%
g. ATCO Callsign Confusion for aircraft Shannon_k	167	14.4%
h. Pilot Cork Departing_k questioning ATCO response	206	17.8%
i. Pilot Shannon_k questioning ATCO response	72	6.2%
j. Pilot Cork Departing_k Callsign Confusion	0	0.0%
k. Pilot Shannon_k Callsign Confusion	0	0.0%

Next, the non-nominal events are further analysed.

c. ATCO Callsign Confusion for aircraft Cork Departing_k

In 261 runs, the ATCO confuses the callsign of the pilot Cork Departing_k with the callsign of the pilot Shannon_k, but no runway incursion is following.

Table 8-4: MC Simulation Results- ATCO callsign confusions for Pilot Cork Departing_k in combination with other non-nominal events

Non-nominal event type occurring in combination with type ATCO Callsign Confusion for aircraft Cork Departing_k	Number of simulation runs
g. ATCO Callsign Confusion for aircraft Shannon_k	1
d. ATCO wrong frequency selection Cork	0
e. ATCO wrong frequency selection Shannon	0
f. ATCO forgets about aircraft Cork Landing_k	0
h. Pilot Cork Departing_k questioning ATCO response	0
i. Pilot Shannon_k questioning ATCO response	0
j. Pilot Cork Departing_k Callsign Confusion	0
k. Pilot Shannon_k Callsign Confusion	0

In one of the 261 one runs, the ATCO does not only confuse the callsign of the pilot Cork Departing_k, but also of the Pilot Shannon_k (simulation run 978,326), see table above.

Looking in detail into the runs, two event patterns can be identified:

- In 169 out of 261 runs, the Pilot Shannon_k requests line up clearance first and the ATCO gives line up clearance immediately (ATCO Task Transition G3.1). Then Pilot Cork Departing_k requests line up clearance as well. However, the ATCO confuses (ATCO Task Transition G2) the callsign of the Pilot Cork Departing_k with the callsign of Pilot Shannon_k and thinks that the Pilot Shannon_k is asking for a confirmation line up clearance. Therefore, the ATCO repeats the line-up clearance (ATCO Task Transition G3.1 again) for Pilot Shannon_k. Pilot Shannon_k does not challenge the repeated instruction because it is the same instruction as before.
- In 92 out of 261 runs, Pilot Cork Departing_k requests a clearance first. However, the ATCO confuses the callsign of the Pilot Cork Departing_k with the callsign of Pilot Shannon_k (ATCO Task Transition G2) and thinks that the Pilot Shannon_k is asking for a line up clearance. Therefore, the ATCO gives the line-up clearance for Pilot Shannon_k (ATCO Task Transition G3.1). Pilot Shannon_k does not challenge the line-up clearance because s/he is at the Departure Holding Point and thinks the ATCO is anticipating the request, or in some cases the Pilot Shannon_k has requested the line-up clearance in the meantime.

Regarding simulation run 978,326 where two callsign confusions occur, the second of the above event pattern types can be identified.

It can be concluded that no runway incursion occurs because the ATCO is still giving the correct instruction to each aircraft of each airport, however s/he communicates with the wrong aircraft (i.e. not the one that contacts him/her). In other words, the ATCO is talking to the wrong aircraft but gives a right instruction.

d. ATCO wrong frequency selection Cork

In 240 MC runs the ATCO wants to select Cork frequency but selects Shannon frequency by mistake, but no runway incursion follows.

Table 8-5: MC Simulation Results- ATCO selection of wrong frequency for Cork in combination with other non-nominal events

Non-nominal event type occurring in combination with type ATCO wrong frequency selection Cork	Number of simulation runs
i. Pilot Shannon_k questioning ATCO response	72
c. ATCO Callsign Confusion for aircraft Cork Departing_k	0
e. ATCO wrong frequency selection Shannon	0
f. ATCO forgets about aircraft Cork Landing_k	0
g. ATCO Callsign Confusion for aircraft Shannon_k	0
h. Pilot Cork Departing_k questioning ATCO response	0
j. Pilot Cork Departing_k Callsign Confusion	0
k. Pilot Shannon_k Callsign Confusion	0

There are two event patterns which can be identified:

- In 72 out of the 240 runs, Pilot Cork Departing_k requests line up clearance. The ATCO responds with a Hold instruction and callsign of Pilot Cork Departing_k but transmits it on the Shannon frequency (ATCO Task Transition G3.1). Then pilot Shannon_k also requests a line up clearance and picks up the instruction of the ATCO, because s/he is waiting for this type of instruction. Since the callsign is incorrect, pilot Shannon_k questions the ATCO about the validity of his/her instruction (ATCO Task Transition G4.2).
- In 168 out of the 240 runs, the Pilot Shannon_k requests line up clearance and the ATCO grants it and the pilot Shannon_k lines up (ATCO Task Transition G3.1). Then Pilot Cork Departing_k requests line up clearance. The ATCO responds with a Hold instruction and callsign of Pilot Cork Departing_k but transmits it on the Shannon frequency (ATCO Task Transition G3.1 again). Pilot Shannon_k does not react upon the instruction because the callsign is not his/hers and s/he is not waiting for a hold or line up instruction by the ATCO anymore. Simulation ends when aircraft in Cork lands.

e. ATCO wrong frequency selection Shannon

In 226 MC runs the ATCO wants to select Shannon frequency but selects Cork frequency by mistake, but no runway incursion follows.

Table 8-6: MC Simulation Results- ATCO selection of wrong frequency for Shannon in combination with other non-nominal events

Non-nominal event type occurring in combination with type ATCO wrong frequency selection Shannon	Number of simulation runs
h. Pilot Cork Departing_k questioning ATCO response	206
c. ATCO Callsign Confusion for aircraft Cork Departing_k	0
d. ATCO wrong frequency selection Cork	0
f. ATCO forgets about aircraft Cork Landing_k	0
g. ATCO Callsign Confusion for aircraft Shannon_k	0
i. Pilot Shannon_k questioning ATCO response	0
j. Pilot Cork Departing_k Callsign Confusion	0
k. Pilot Shannon_k Callsign Confusion	0

There are two event patterns which can be identified:

- In 206 out of the 226 runs, Pilot Shannon_k requests line up clearance. The ATCO responds with a line up clearance and callsign of Pilot Shannon_k but transmits it on the Cork frequency (ATCO Task Transition G3.2). Then pilot Cork Departing_k also requests a line up clearance and picks up the instruction of the ATCO, because s/he is waiting for this type of instruction. Since the callsign is incorrect, pilot Cork Departing_k questions the ATCO about the validity of his/her instruction (ATCO Task Transition I4.2).
- In 20 out of the 226 runs, pilot Shannon_k requests line up clearance. The ATCO responds with a line up clearance and callsign of Pilot Shannon_k but transmits it on the Cork frequency (ATCO Task Transition G3.2). Then Pilot Cork Departing_k requests line up clearance. The same outcome as per the previous pattern is expected, however the pilot Cork Departing_k does not question the ATCO because the selection of the wrong frequency occurs right before the aircraft in Cork landed. Therefore, did not give the chance for the pilot Cork Departing_k to question.

f. ATCO forgets about aircraft Cork Landing_k

In 221 MC runs the ATCO forgets about the aircraft landing in Cork, but no runway incursion follows.

Table 8-7: MC Simulation Results- ATCO forgets about aircraft Cork Landing_k in combination with other non-nominal events

Non-nominal event type occurring in combination with type ATCO forgets about aircraft Cork Landing_k	Number of simulation runs
c. ATCO Callsign Confusion for aircraft Cork Departing_k	0
d. ATCO wrong frequency selection Cork	0
e. ATCO wrong frequency selection Shannon	0
g. ATCO Callsign Confusion for aircraft Shannon_k	0
h. Pilot Cork Departing_k questioning ATCO response	0
i. Pilot Shannon_k questioning ATCO response	0
j. Pilot Cork Departing_k Callsign Confusion	0
k. Pilot Shannon_k Callsign Confusion	0

There are ten event patterns which can be identified:

- In 118 out of the 221 runs, the pilot Shannon_k requests the line-up first (ATCO Task Transition I1) and the ATCO gives line up clearance (ATCO Task Transition G3.1).
    - In 63 out of the 118 runs, after the pilot Shannon_k is lining up, the ATCO also gives a line up clearance to pilot Cork Departing_k (ATCO Task Transition G3.2), then the pilot reads back the clearance (ATCO Task Transition I4.2).
    - In 27 out of the 118 runs, after the pilot Shannon_k is lining up, the ATCO also gives a line up clearance to pilot Cork Departing_k (ATCO Task Transition G3.2), then the pilot reads back the clearance. In addition to the simulation results above, before the giving the line-up clearance, the ATCO also gives a hold message to the pilot Cork Departing_k (ATCO Task Transition G3.2 again). This occurs because the ATCO forgets about the aircraft landing after s/he communicated with the pilot Cork Departing_k.
    - In 2 out of the 118 runs, after the pilot Shannon_k is lining up, the pilot Cork Departing_k is asking for a line up clearance. However, the simulation ends before the ATCO can give a clearance to pilot Cork Departing_k.
    - In 11 out of 118 runs, after the pilot Shannon_k is lining up, the pilot Cork Departing_k is asking for a line up clearance and the ATCO gives the line-up clearance (ATCO Task Transition G3.2). The simulation ends before the pilot could readback to the ATCO, i.e. to respond to the line-up clearance.

  - In 15 out of 118 runs, after the pilot Shannon_k is lining up, the ATCO is giving the pilot Cork Departing_k a line up clearance (ATCO Task Transition G3.2). In addition to the simulation results above, before the giving the line-up clearance, the ATCO also gives a hold message to the pilot Cork Departing_k (ATCO Task Transition G3.2 again). This occurs because the ATCO forgets about the aircraft landing after s/he communicated with the pilot Cork Departing_k. The simulation ends before the pilot could readback to the ATCO, i.e. to respond to the line-up clearance.

- In 103 out of the 221 runs, the pilot Cork Departing_k is the one requesting the line-up first (ATCO Task Transition I1).
  - In 63 out of the 103 runs above, the ATCO gives the line-up clearance to pilot Cork Departing_k (ATCO Task Transition G3.2), then the pilot reads back the clearance (ATCO Task Transition I4.2).
  - In 26 out the 103 runs above, the ATCO gives the line-up clearance to pilot Cork Departing_k(ATCO Task Transition G3.2), then the pilot reads back the clearance(ATCO Task Transition I4.2). In addition to the simulation results above, before the giving the line-up clearance, the ATCO also gives a hold message to the pilot Cork Departing_k (ATCO Task Transition G3.2 again). This occurs because the ATCO forgets about the aircraft landing after s/he communicated with the pilot Cork Departing_k.
  - In 1 out of 103 runs above, the pilot Cork Departing_k is asking for a line up clearance (ATCO Task Transition I1). However, the simulation ends before the ATCO can give a clearance to pilot Cork Departing_k.
  - In 7 out of 103 runs, the pilot Cork Departing_k is asking for a line up clearance(ATCO Task Transition I1). The ATCO forgets about the aircraft Cork Landing_k and gives a line up clearance (ATCO Task Transition G3.2). The simulation ends before the pilot could readback to the ATCO, i.e. to respond to the line-up clearance.
  - In 6 out of 103 runs, the simulation ends before the pilot could readback to the ATCO, i.e. to respond to the line-up clearance(ATCO Task Transition G3.2). In addition to the simulation results above, in these runs the ATCO communicates with the pilot Cork Departing_k, giving a hold message to the pilot (ATCO Task Transition G3.2 again). This occurs because the ATCO forgets about the aircraft landing after s/he communicated with the pilot Cork Departing_k.

While none of these non-nominal events result in a runway incursion, it is unclear whether this is due to the fact that the pilot has landed. For the situation where the pilot Cork Departing_k reads back the line-up clearance (179 out of the 221), it is unclear whether the pilot Cork Departing_k is aware of the aircraft landing, and confirms the clearance taking into account that the line-up will occur after the aircraft lands, or if the pilot Cork Departing_k is not aware and it starts lining up but the simulation ends before the runway incursion can occur.

g. ATCO Callsign Confusion for aircraft Shannon_k

In 167 runs, the ATCO confuses the callsign of the pilot Shannon_k with the callsign of the pilot Cork Departing_k but no runway incursion is following.

Table 8-8: MC Simulation Results- ATCO callsign confusions for Pilot Shannon_k in combination with other non-nominal events

Non-nominal event type occurring in combination with type ATCO callsign confusions for Pilot Shannon_k	Number of simulation runs
c. ATCO Callsign Confusion for aircraft Cork Departing_k	1
d. ATCO wrong frequency selection Cork	0
e. ATCO wrong frequency selection Shannon	0
f. ATCO forgets about aircraft Cork Landing_k	0
h. Pilot Cork Departing_k questioning ATCO response	0
i. Pilot Shannon_k questioning ATCO response	0
j. Pilot Cork Departing_k Callsign Confusion	0
k. Pilot Shannon_k Callsign Confusion	0

In one of the 167 one runs, the ATCO does not only confuse the callsign of the pilot Shannon_k, but also of the Pilot Cork Departing_k (simulation run 978,326), see table above.

Looking in detail into the runs, two event patterns can be identified:

- In 54 out of 167 runs, Pilot Cork Departing_k requests a line up clearance first(ATCO Task Transition I1) and the ATCO gives a hold clearance immediately (ATCO Task Transition G3.2). Then Pilot Shannon_k also requests a line up clearance. However, the ATCO confuses the callsign of the Pilot Shannon_k with the callsign of Pilot Cork Departing_k and thinks that the Pilot Cork Departing_k is asking for a line up clearance again (ATCO Task Transition G2). Therefore, the ATCO repeats the hold instruction for Pilot Cork Departing_k(ATCO Task Transition G3.2 again). Pilot Cork Departing_k does not challenge the repeated instruction because it is the same instruction as before.
- In 113 out of 167 runs, the Pilot Shannon_k requests a line up clearance first (ATCO Task Transition I1). However, the ATCO confuses the callsign of Pilot Shannon_k with the callsign of the Pilot Cork Departing_k and thinks that the Pilot Cork Departing_k is asking for a line up clearance (ATCO Task Transition G2). Therefore, the ATCO gives the hold instruction for Pilot Cork Departing_k (ATCO Task Transition G3.2). Pilot Cork Departing_k does not challenge the hold instruction because s/he is at the Departure Holding Point and thinks the ATCO is anticipating the request, or in some cases the Pilot Cork Departing_k has requested the line-up clearance in the meantime.

Regarding the special case, simulation run 978,326 this was no different to the first event pattern type identified above.

It can be concluded that no runway incursion occurs because the ATCO is still giving the correct instruction to each aircraft of each airport, however s/he communicates with the wrong aircraft (i.e. not the one that contacted him/her). In other words, the ATCO is giving to the wrong aircraft, a right instruction.

h. Pilot Cork Departing_k questioning ATCO response

In 206 simulation runs the pilot Cork Departing_k questions the ATCO response, and no runway incursion is following.

Table 8-9: MC Simulation Results- Pilot Cork Departing_k questions the ATCO in combination with other non-nominal events

Non-nominal event type occurring in combination with type Pilot Cork Departing_k questioning ATCO response	Number of simulation runs
e. ATCO wrong frequency selection Shannon	206
c. ATCO Callsign Confusion for aircraft Cork Departing_k	0
d. ATCO wrong frequency selection Cork	0
f. ATCO forgets about aircraft Cork Landing_k	0
g. ATCO Callsign Confusion for aircraft Shannon_k	0
i. Pilot Shannon_k questioning ATCO response	0
j. Pilot Cork Departing_k Callsign Confusion	0
k. Pilot Shannon_k Callsign Confusion	0

In all (206 simulation runs), the reason for the pilot Cork Departing_k questioning ATCO (Pilot Task transition I4) message is that the ATCO sends the message (ATCO Tasks Transition G3.2) for the pilot Shannon_k on the Cork frequency and pilot Cork Departing_k notices the different callsign, see table above.

i. Pilot Shannon_k questioning ATCO response

In 72 simulation runs the pilot Shannon_k questions the ATCO response, and no runway incursion is following.

Table 8-10: MC Simulation Results- Pilot Shannon_k questions the ATCO in combination with other non-nominal events

Non-nominal event type occurring in combination with type Pilot Shannon_k questioning ATCO response	Number of simulation runs
d. ATCO wrong frequency selection Cork	72
c. ATCO Callsign Confusion for aircraft Cork Departing_k	0
e. ATCO wrong frequency selection Shannon	0
f. ATCO forgets about aircraft Cork Landing_k	0
g. ATCO Callsign Confusion for aircraft Shannon_k	0
h. Pilot Cork Departing_k questioning ATCO response	0
j. Pilot Cork Departing_k Callsign Confusion	0
k. Pilot Shannon_k Callsign Confusion	0

In all (72 simulation runs), the reason for the pilot Shannon_k questioning ATCO message (Pilot Task Transition I4) is that the ATCO sends the message for the pilot Cork Departing_k on the Shannon frequency (ATCO Tasks Transition G3.1) and pilot Shannon_k notices the different callsign, see table above.

j. Pilot Cork Departing_k Callsign Confusion

None of the simulation runs has the pilot Cork Departing_k confusing the message received and thinking that the message it for him/her.

This would result if the ATCO sends the message on the wrong frequency (message for pilot Shannon_k sent on the Cork frequency) or the ATCO sending the message to pilot with a wrong callsign (ATCO callsign confusion for pilot Cork Departing_k). This is captured in the Pilot Task Transition I4.

k. Pilot Shannon_k Callsign Confusion

None of the simulation runs has the pilot Shannon_k confusing the message received and thinking that the message it for him/her.

This would result if the ATCO sends the message on the wrong frequency (message for pilot Cork Departing_k sent on the Shannon frequency) or ATCO sending the message to pilot with a wrong callsign (ATCO callsign confusion for pilot Shannon_k). This is captured in the Pilot Task Transition I4.

8.5 Do these incidents happen in current operation?

This section compares the results of the MC simulation against the current incident data as it is reported by IAA. These results are also discussed with the SMEs, as described in chapter 11.

Firstly, the results of the MC simulation were validated against the IAA incident data. The incidents considered here were from the IAA incident database, from 2013- 2019 inclusive.

In terms of the runway incursions in Cork, there were 31 incidents reported. Out of these incidents, there were two incidents where the causal factor was ATCO forgetting about the pilot landing. The first runway incursion occurred due to ATCO's vision being obstructed from the tower, i.e. there is a blind spot in the current tower window due to a stress beam in the tower. The second runway incursion occurred due to the ATCO being confused to where the pilot landing is located and giving line up clearance to the pilot departing using non-standard phraseology.

In terms of the non-nominal events, there were no incidents in either Shannon or Cork involving selection of frequency for the other airport, since this is not possible in local tower.

For the callsign confusion, incident data shows that there were no callsign confusions reported for these airports.

The SMEs have indicated that callsign confusions do occur in both Shannon and Cork, however the ATCO will correct him/herself immediately and due to the fact that the callsign confusion did not results in an incident, the ATCO would not report it.

Given there are no reported callsign confusions, there are no reported incidents where the pilots question the ATCO.

9. Comparison of MC simulation counts vs. safety criteria

This section analyses the non-nominal events against safety criteria to determine whether the risk associated with these events is acceptable or not acceptable. This represents Step 6 of Figure 1-2.

9.1 FAA Risk Criteria

The safety criteria used for this assessment is the FAA risk classification scheme. While the IAA risk classification scheme is also available, it is solely looking at the risk from the provision of ATC service. In other words, the highest severity incident is the one where the ATCO has lost the ability to provide air traffic control service. While this might be relevant from the ATC perspective, it is important to understand the risk from the entire operation standpoint, and not solely ATCO. For that reason, the FAA Risk Matrix is used. This is a well-established industry risk classification scheme. Moreover, the EU 2017/373 regulation allows service providers to use other recognised standards/code of practice as safety criteria (European Aviation Safety Agency, 2017).

The FAA risk Classification scheme is described below. A risk matrix is comprised of severity and probability, and the risk results from the combination of both (Federal Aviation Administration, 2017).

The FAA severity classes, and their definition are presented below.

Minimal 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Negligible safety effect	– Physical discomfort to persons – Slight damage to aircraft/vehicle	– Physical distress or injuries to persons – Substantial damage to aircraft/vehicle	Multiple serious injuries; fatal injury to a relatively small number of persons (one or two); or a hull loss without fatalities	Multiple fatalities (or fatality to all on board) usually with the loss of aircraft/ vehicle

Figure 9-1: Severity Definitions (Federal Aviation Administration, 2017)

The FAA probability/likelihood classes, and their definition are presented below.

	Qualitative	Quantitative – Time/Calendar-based Occurrences Domain-wide/System-wide
Frequent A	Expected to occur routinely	Expected to occur more than 10 times per year
Probable B	Expected to occur often	Expected to occur between one and 10 times per year
Remote C	Expected to occur infrequently	Expected to occur one time every 1 to 3 years
Extremely Remote D	Expected to occur rarely	Expected to occur one time every 3 to 10 years
Extremely Improbable E	Unlikely to occur, but not impossible	Expected to occur less than once every 10 years

Figure 9-2: Probability/Likelihood Definitions (Federal Aviation Administration, 2017)

The risk matrix, containing the severity and likelihood combinations is presented below.

Severity / Likelihood	Minimal 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Frequent A	[Green]	[Yellow]	[Red]	[Red]	[Red]
Probable B	[Green]	[Yellow]	[Red]	[Red]	[Red]
Remote C	[Green]	[Yellow]	[Yellow]	[Red]	[Red]
Extremely Remote D	[Green]	[Green]	[Yellow]	[Yellow]	[Red]
Extremely Improbable E	[Green]	[Green]	[Green]	[Yellow]	[Red] * / [Yellow]

High Risk [Red]
Medium Risk [Yellow]
Low Risk [Green]

* High Risk with Single Point and/or Common Cause Failures

Figure 9-3: Risk Matrix (Federal Aviation Administration, 2017)

Before assessing the risk, it is important to identify the likelihood whether the MC simulation scenario to occur.

A traffic analysis was conducted to estimate the probability of the MC simulation scenario to occur. The results were also discussed with the SMEs. The maximum amount of traffic that can be subjected to this scenario represents the minimum traffic/year in either Shannon (±25,000 flights) or Cork (±50,000 flights). The traffic in Shannon is ±25,000 flights/year, which translates to ±12,500 departures. It is hard to estimate how many times the scenario will occur given that the type of traffic in Cork, i.e. more than 70% is unscheduled. However, the traffic distribution analysis shows that most of the traffic is concentrated in the core morning and afternoon hours.

The traffic analysis was also discussed with the SME in the brainstorming activities. It is concluded that around 5,000 flights per year will potentially have two aircraft lining up at the same time.

The 1,000,000 runs from the MC simulation, assuming the traffic levels will remain constant, are therefore the equivalent of 200 years of traffic.

9.2 Fitting the Runway Incursion in the FAA Risk Matrix

While not all runway incursions will result in runway collisions, all of them impose a risk to the operations.

As presented in chapter 8 , the runway incursions' severity can be classified based on the remaining time to land in:

a. Runway incursions occurring when aircraft Cork Landing_k is less than 40 seconds from landing

There are 17 runway incursions occurring within 40 seconds from landing. For these 17 cases there is a large chance that the remaining time is too short for the pilot Cork-landing to initiate a go-around.

The severity of these is Severity 1: Catastrophic, as it is estimated that all of them will result in an accident, a runway collision. The probability of these incidents is Extremely Remote: D. The risk associated is **High Risk [red]**.

b. Runway incursions occurring when aircraft Cork Landing_k is at or more than 40 seconds from landing

There are 28 runway incursions when aircraft is at more than 40 seconds. These runway incursions occur when the pilot Cork Landing_k is more than 40 seconds from landing which gives enough time to initiate avoiding action for pilot Cork Landing_k.

The severity of these is Severity 3: Major, as it is estimated that none of them would result in an accident, due to the distress that the ATCO and pilots will encounter. The probability of these incidents is Extremely Remote: D. The risk associated is **Medium Risk [Yellow]**.

Next, the non-nominal events that did not result in a runway incursion are risk assessed.

9.3 Fitting the other non-nominal events in the FAA Risk Matrix

While the non-nominal events do not result in a runway incursion, they still affect the operations and can impose a threat to safety.

This section presents the risk assessment of the non-nominal events. The non-nominal events and their associated risk are:

c. ATCO Callsign Confusion for aircraft Cork Departing_k

In 261 runs, the ATCO confuses the callsign of the pilot Cork Departing_k with the callsign of the pilot Shannon_k but no runway incursion is following. No runway incursion occurs because the ATCO is still giving the correct instruction to each aircraft of each airport, however s/he communicates with the wrong aircraft (i.e. not the one that contacts him/her). In other words, the ATCO is talking to the wrong aircraft but gives a right instruction.

The severity of these is Severity 5: Minimal, as there is no wrong instruction given to the pilots. The probability of these incidents is Remote: C. The risk associated is **Low Risk [Green]**.

d. ATCO wrong frequency selection Cork

In 240 MC runs the ATCO wants to select Cork frequency but selects Shannon frequency by mistake, but no runway incursion follows. No runway incursion occurs because either the Pilot Shannon_k question ATCO or the simulation ends before the pilot can respond.

The severity of these is Severity 4: Minor, as this represents an increase in ATCO and pilot confusion and can increase workload and ATCO distress. The probability of these incidents is Remote: C. The risk associated is **Medium Risk [Yellow]**.

e. ATCO wrong frequency selection Shannon

In 226 MC runs the ATCO wants to select Shannon frequency but selects Cork frequency by mistake, but no runway incursion follows.

No runway incursion occurs because either the Pilot Cork Departing_k questions the ATCO or the simulation ends before the pilot can respond.

The severity of these is Severity 4: Minor, as this represents an increase in ATCO and pilot confusion and can increase workload and ATCO distress. The probability of these incidents is Remote: C. The risk associated is **Medium Risk [Yellow]**.

f. ATCO forgets about aircraft Cork Landing_k

In 221 MC runs the ATCO forgets about the aircraft landing in Cork, but no runway incursion follows. While none of these non-nominal events result in a runway incursion, it is unclear whether this is because the pilot has landed before the pilot Cork Departing_k could start lining up. For the situation where the pilot Cork Departing_k reads back the line-up clearance (179 out of the 221), it is unclear whether the pilot Cork Departing_k is aware of the aircraft landing, and confirms the clearance taking into account that the line-up will occur after the aircraft lands, or whether the pilot Cork Departing_k is not aware and starts lining up but the simulation ends before the runway incursion can occur.

The severity of these is Severity 3: Major, as this represents an increase in ATCO and pilot confusion and can increase workload and ATCO distress. Also, ATCO forgetting about the aircraft landing is the highest contributor to runway incursions, which is clearly very dangerous. The probability of these incidents is Remote: C. The risk associated is **Medium Risk [Yellow]**.

g. ATCO Callsign Confusion for aircraft Shannon_k

In 167 runs, the ATCO confuses the callsign of the pilot Shannon_k with the callsign of the pilot Cork Departing_k, in the runs, but no runway incursion is following. No runway incursion occurs because the ATCO is still giving the correct instruction to each aircraft of each airport, however s/he communicates with the wrong aircraft (i.e. not the one that contacts him/her). In other words, the ATCO is talking to the wrong aircraft but gives a right instruction.

The severity of these is Severity 5: Minimal, as there is no wrong instruction given to the pilots. The probability of these incidents is Remote: C. The risk associated is **Low Risk [Green]**.

h. Pilot Cork Departing_k questioning ATCO response

In 206 simulation runs the pilot Cork Departing_k questions the ATCO response, and no runway incursion is following. This non-nominal event comes in response to an ATCO wrong instruction. However, questioning the ATCO lowers confidence from the pilots in air traffic control, and this mistrust might result in operational deviance, i.e. pilot ignoring or questioning the ATCO more in the future.

As this is unknown now, the severity of these is Severity 5: Minimal and the probability of these incidents is Remote: C. The risk associated is **Low Risk [Green]**

i. Pilot Shannon_k questioning ATCO response

In 206 simulation runs the pilot Shannon_k questions the ATCO response, and no runway incursion is following. This non-nominal event comes in response to an ATCO wrong instruction. However, questioning the ATCO lowers confidence from the pilots in air traffic control, and this mistrust might result in operational deviance, i.e. pilot ignoring or questioning the ATCO more in the future.

As this is unknown now, the severity of these is Severity 5: Minimal and the probability of these incidents is Remote: C. The risk associated is **Low Risk [Green]**

j. Pilot Cork Departing_k Callsign Confusion

None of the simulation runs has the pilot Cork Departing_k confusing the message received and thinking that the message is for him/her. The severity of these is Severity 5: Minimal and the probability of these incidents is Extremely Improbable: E. The risk associated is **Low Risk [Green]**

k. Pilot Shannon_k Callsign Confusion

None of the simulation runs has the pilot Shannon_k confusing the message received and thinking that the message is for him/her. The severity of these is Severity 5: Minimal and the probability of these incidents is Extremely Improbable: E. The risk associated is **Low Risk [Green]**

In summary, Figure 9-4 below presents the distribution of the risks of the MC simulation counts.

Severity / Likelihood	Minimal 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Frequent A					
Probable B					
Remote C	**c, g, h, i**	**d, e**	**f**		
Extremely Remote D			**b**		**a**
Extremely Improbable E	**j, k**				

Figure 9-4: Summary of Risks of the MC simulation counts

The results indicate that there are:

- **1 High Risk [Red]** from the **a**. Runway incursions occurring when aircraft Cork Landing_k is less than 40 seconds from landing
- **4 Medium Risks [Yellow]** resulting from:

  b. Runway incursions occurring when aircraft Cork Landing_k is at or more than 40 seconds from landing

  d. ATCO wrong frequency selection Cork

  e. ATCO wrong frequency selection Shannon

  f. ATCO forgets about aircraft Cork Landing_k
- **6 Low Risks [Green]** resulting from:

  c. ATCO Callsign Confusion for aircraft Cork Departing_k

  g. ATCO Callsign Confusion for aircraft Shannon_k

  h. Pilot Cork Departing_k questioning ATCO response

i. Pilot Shannon_k questioning ATCO response

j. Pilot Cork Departing_k Callsign Confusion

k. Pilot Shannon_k Callsign Confusion

10. Identification of safety bottlenecks

The results have indicated that runway incursions and potential collisions may be expected in a multiple remote tower environment. This chapter presents the bottlenecks for multiple remote tower operations. This represents Step 7 of Figure 1-2.

As per chapter 9 above, the risk associated with multiple remote tower operation is high, so mitigations have to be put in place to ensure the operations are at least as safe as before. The mitigation strategy is focussed on lowering the number High Risks [Red] and Medium Risks [Yellow].

From Figure 9-4, there are 1 High Risk [Red] and 5 Medium Risks [Yellow], which include:

- **1 High Risk [Red]** from the **a**. Runway incursions occurring when aircraft Cork Landing_k is less than 40 seconds from landing

- **4 Medium Risks [Yellow]** resulting from:

  b. Runway incursions occurring when aircraft Cork Landing_k is at or more than 40 seconds from landing

  d. ATCO wrong frequency selection Cork

  e. ATCO wrong frequency selection Shannon

  f. ATCO forgets about aircraft Cork Landing_k

Table 10-1 presents the distribution of bottlenecks for the runway incursions and other non-nominal events.

Table 10-1: Bottlenecks distribution per non-nominal event

	Bottleneck	
	ATCO forgets about the pilot Cork Landing_k	ATCO selects the wrong frequency
a. Runway incursions occurring when aircraft Cork Landing_k is less than 40 seconds from landing	✓	✓
b. Runway incursions occurring when aircraft Cork Landing_k is at or more than 40 seconds from landing	✓	
d. ATCO wrong frequency selection Cork		✓
e. ATCO wrong frequency selection Shannon		✓
f. ATCO forgets about aircraft Cork Landing_k	✓	

The two bottlenecks for this MC scenario are that the ATCO forgets about the pilot landing and gives a line up instruction to the pilot at departure holding point, and ATCO selection of wrong frequency. These trigger all the non-nominal events resulting in both High and Medium risks.

The first bottleneck, i.e. ATCO forgetting about the aircraft Cork Departing Landing_k is contributing to all runway incursions described above. It also occurs in an additional 221 MC simulation runs that did not result in a runway incursion. This bottleneck leads to a MASA difference of ATCO about the location of pilot Cork Landing_k in ATCO Task Transition G2, i.e. when the ATCO checks both aerodromes to decide what clearance to give.

The second bottleneck is the ATCO selecting the wrong frequency. This occurs in one runway incursion. Moreover, in this runway incursion the ATCO also forgets about the landing aircraft, and even mistakenly selecting the wrong frequency once does not result in the recovery in the situation awareness difference.

ATCO selecting the wrong frequency also occurs in additional 466 non-nominal events that do not result in a runway incursion, where in 240 times the ATCO selects Shannon frequency by mistake, and in the remaining 226 s/he selects Shannon by mistake. This bottleneck leads to a MASA difference of ATCO about the selected frequency of an airport in ATCO Task Transition G2, i.e. when the ATCO decides what frequency to give a clearance on but selects the wrong one.

Finally, these bottlenecks were discussed with operational SME as part of a brainstorming session to identify possible improvements for multiple remote tower operations.

11. Brainstorming possible improvements for the real operation

This section provides the outcomes of brainstorming activities with subject matter experts (SMEs) for possible improvements for multiple remote tower operations, by addressing the bottlenecks identified in the MC simulation. This represents Step 8 of Figure 1-2.

As part of this step a brainstorming activity was conducted with operational SME.

The objective of the brainstorming activity was:

- To present the results of the MC simulation;
- To analyse and interpret the results using SME input;
- To discuss the identified bottlenecks with the aim for the SME to propose possible improvements, if necessary, for multiple remote tower operations.

Prior to brainstorming, a presentation was given to the SME containing the summary of the results and main findings.

Second, the results were analysed and interpreted using SME input.

With the current traffic distribution in both Shannon and Cork airport, the SMEs have concluded that this scenario (two aircraft waiting at Departure Holding Point, with a third one on final approach) can occur approximately 5,000 times in a year. This information was used in assessing the risk of the non-nominal events against safety criteria in chapter 9.

The results were discussed with the SMEs, to compare with the current manned tower operations. SMEs have indicated that runway incursions due to ATCO forgetting about the landing aircraft occurred, as well as callsign confusions. In terms of selection of wrong frequency, this is not a current feature of the operations, but they did indicate that this type of incidents would be expected as it occurred in the IAA Large Scale Demonstration.

The SME input was necessary in analysing the runway incursions and what is considered enough time to initiate avoiding action for the pilot landing in Cork. The SMEs input was that 30 seconds is the cut-off time for a successful go-around in Cork airport. The time was decided from:

- Predominant fleet of CAT C aircraft (e.g. Boeing 737 and Airbus A320)
- Predominant runway (RWY 16)
- Predominant CAT II approach, with a decision height (DH) of 100 ft.
- Predominant weather expected in Cork, which is usually a very low cloud, it is estimated that the pilot landing will be unable to see the Pilot Cork Departing_k lining up just before DH.

This information was used in chapter 8, in the analysis of the simulation runs that lead to a runway incursion.

Third, the bottlenecks were discussed with the SMEs. The SMEs have indicated that, as part of the IAA Large Scale Demonstration for Multiple Remote Tower (Irish Aviation Authority, 2016), possible improvements were proposed. The SME have taken advantage of this knowledge in this bottleneck discussion.

For the first bottleneck identified in the MC simulation, i.e. the ATCO forgetting about the pilot Cork Departing Landing_k and giving a line up instruction to the pilot in Cork, this did not occur in the large scale demonstration, and therefore this is an important new result from the simulation as this MASA difference was the largest contributor to runway incursions and collisions. It was however identified that monitoring aircraft is more difficult from the remote tower than local tower, due to being harder to monitor smaller aircraft, fast moving aircraft and monitoring aircraft at night. The SMEs have indicated that these will all contribute to the ATCO forgetting about the landing aircraft.

The SMEs have identified the following possible improvements that could be implemented to ensure that the ATCO does not forget about the aircraft landing:

- Improvement of the out of the window (OTW) view for landing traffic. The SMEs have indicated that the landing traffic in the large-scale demonstration quite often did not show up. If on the screen the aircraft location was not moving for a while (due to screen resolution), the box around the aircraft (current feature in the remote tower to show a moving target) disappeared. As possible improvement, if an object is detected a moving the box should remain around the object even if the object appears not to be moving for a while.
- For night-time approaches, it was difficult to determine whether the aircraft had landed which was not a problem in the local tower. Potential improvement might be changing the camera location or improvement in the video quality.
- Improvement of the automatic object tracking capability. This was less useful in darkness than in daylight. This is due to the increasing light surrounding the airports at night.
- Improvement by introducing changes to operating methods/procedures, or even change to how the remote tower system operates.
- Improvement by introduction of Electronic Flight Strips (EFS). Currently none of the towers have EFS, however the large-scale demonstration was performed using EFS. This was very well received by ATCOs, who agreed that if the EFS is kept up to date with the latest operational picture, it provides safety benefits which the paper strips do not provide.
- Improvement by limiting the simultaneous movement. The SMEs stated that it is very difficult to establish the optimum number of movements due to difference in types of movements (IFR vs VFR, scheduled vs non-scheduled etc) which might induce an unpredictable increase in workload.
- Improvement in the pan-tilt-zoom (PTZ) camera which is meant to replace binoculars. The remote tower screens show aircraft smaller compared to the current local towers. This makes it difficult to see smaller objects far away from the camera. The PTZ camera is important for monitoring hotspots or checking aircraft landing. SMEs have indicated that using the PTZ camera increases ATCO workload, which does not exist in the local tower, i.e. PTZ is needed more frequently than binoculars.

For the second bottleneck, the SMEs have identified the following improvements that could be implemented:

- Improvement in the form of visual cues (overlays) on the OTW, such as outlining the runways, taxiways etc. This was especially needed at night, because there are no visual references to differentiate between Cork and Shannon.
- Improvement to alert the ATCO to the possibility of call sign similarity with aircraft on different airports.
- Improvement in frequency use. During the large-scale demonstration trials there was a high level of noise in the RTC when a single ATCO had to operate four frequencies and monitoring an additional two frequencies. This increased the confusion for the ATCO.
- Improvement in operations planning. The large-scale demonstration highlighted that all four ATCO roles (2 x Air Movements Controller-AMC and 2 x Surface Movements Controller-SMC) could only be carried out by one single ATCO when the traffic was light. However, what was also highlighted is that it was not feasible for one ATCO to control the two AMC positions while another ATCO controlled the two SMC positions as this would involve a significant amount of cross coordination. Therefore, having a threshold to stop multiple remote tower operations is needed.
- Implementing a form of extended phraseology. An extended phraseology was used during the large-scale demonstration. However, the results have indicated a very high increase in the frequency occupancy (RT time) especially in the busy period and therefore alternatives should be sought. Other extended phraseology should be trialled.

As a general comment from the SMEs, it is important to increase awareness for the pilots that multiple remote tower operations are in use so that they are encouraged to question any clearance that does not sound like a clearance they will expect to be transmitted on the frequency.

All the proposed improvements are of course possible. However, before implementation, it has to be verified that these improvements are effective, i.e. that due to implementation no additional hazards are introduced which may pose new risks.

12. Conclusion

The focus of the MSc. Thesis is to develop an agent-based model for multiple remote tower in Shannon and Cork Airport from one remote tower location in Dublin Airport.

The MSc. Thesis is structured following the steps of a safety risk assessments as presented in Figure 1-2.

Chapter 2 represents the acquisition of the information through desk research. The purpose of the research is to acquire knowledge and understanding of the remote tower operations, to contribute to the refinement and definition of the scenario for the agent-based model. The materials used for the desk research include both currently available literature and secondary data (airport traffic and safety statistics). The results and outcomes of this research step are recorded in the literature study. The literature study shows that there is no available model looking into multiple remote tower operations. Therefore, developing an agent-based model can provide additional insight into the feasibility of this new concept of air traffic operations. It can be also be utilised in safety cases to assess the safety level of multiple remote tower operations.

Next, in chapter 3, the concept of operation for the multiple remote tower, and an overview of the current operations in Shannon and Cork are presented. Understanding the operational environment and the concept of operations represents the foundation for the hazard identification process, and the agent-based modelling.

Chapter 4 presents hazard identification and initial assessment for multiple remote tower operations. The aim of this step is to identify and select hazard(s) for further analysis and modelling. There are 8 hazards identified for multiple remote tower, that based on the initial assessment can pose a high risk on the multiple remote tower operation. Out of the 8 hazards, two hazards have been chosen for further analysis, i.e. Hazard 3a Instruction given on wrong frequency (another airport than intended) and Hazard 3b Incorrect instruction (different than intended) given on wrong frequency (another airport than intended).

In chapter 5, a scenario for Hazard 3a and Hazard 3b is constructed. The purpose of this activity is to deduct a scenario where these hazards are expected to have the worst consequences, if encountered. The scenario development includes a decision on multiple elements. These elements include: the number of aerodromes, existing safety nets, number of ATCOs, type of communications, number of aircraft involved and their location, callsign similarity, and ATCO and pilots' failure modes. The scenario chosen involves two aerodromes under control (Shannon and Cork), with no safety nets present at either of them. There is one ATCO providing control to three aircraft: one in Shannon at Departure Holding Point, and two in Cork, one at Departure Holding Point and one on final approach having landing clearance. The failure modes for the ATCO include giving the wrong instruction to the aircraft and/or using the wrong frequency to transmit that instruction. The failure modes for the pilots at Departure Holding Point include following a wrong instruction (e.g. for the pilot in Cork to line up) and/or following an instruction not for intended for them(with wrong callsign).

Next, an agent-based model is developed. Chapter 6 provides the description of the agent-based model for multiple remote tower, with an overview of the relevant agents. Multi-agent Situation Awareness (MASA) is also presented in chapter 6. The agent-based model contains 12 agents: ATCO, Pilot Cork Landing_k, Pilot Cork Departing_k, Pilot Shannon_k, Aircraft Cork Landing_k, Aircraft Cork Departing_k, Aircraft Shannon_k, Aircraft Cork Landing_k, Aircraft Cork Departing_k, Aircraft Shannon_k, Communication System Cork, Communication System Shannon, and Remote Tower System. There are also 2 Interconnecting Petri Nets, Frequency Cork and Frequency Shannon.

Chapter 7 describes the petri net model for multiple remote tower, followed by the MATLAB implementation strategy. Details on the petri net model are presented in Appendix E of the MSc. Thesis. As part of the MATLAB implementation strategy, the assumptions considered for the MC simulation as also presented in this chapter.

Chapter 8 presents the MC scenario being simulated and the MC simulation results. It also contains an analysis of simulation runs which lead to runway incursions and the other non-nominal events. A comparison of the results against current airport operation is also performed.

The MC scenario being simulated is described. For each MC run, the initial conditions for the aircraft and ATCO involved, the parameter values adopted, the stop conditions and the results collected, are presented.

A Monte Carlo (MC) simulation of 1,000,000 runs has been conducted. An overview of the results is provided, including an analysis of the runway incursion and other non-nominal events.

The high-level simulation results show that in 998,841 out of 1,000,000 simulation runs no non-nominal event occurs (approximately 99.88%). In the remaining 1,159 simulation runs a runway incursion or other non-nominal events occur (approximately 0.12%).

Of the 1,159 simulation runs, only 45 runs (approximately 0.0005% of total number of runs) result in a runway incursion at Cork airport and 1,114 other non-nominal events (approximately 0.111% of total number of runs).

The MC results have been also compared with the current incident statistics. While runway incursions do occur, only two in the last 6 years have occurred in similar conditions to the one in the MC simulation. In terms of the other non-nominal events, none of them have been reported. However, the SMEs have indicated that callsign confusions do occur, while the other non-nominal events are solely related to the multiple operations.

In Chapter 9, an analysis of the runway incursions and the other non-nominal events against safety criteria is performed. The objective of the analysis is to determine whether the risk associated with these events is acceptable.

Firstly, the safety criteria are chosen. The safety criteria used for this assessment are defined in the FAA Risk Matrix. While the IAA risk classification scheme is also available, it is solely looking at the risk from the provision of ATC service. In other words, the highest severity incident is the one where the ATCO has lost the ability to provide air traffic control service. While this might be relevant from the ATC perspective, it is important to understand the risk from the entire operation standpoint, and not solely ATCO. For that reason, the FAA Risk Matrix is used. This is a well-established industry risk classification scheme. Moreover, the EU 2017/373 regulation allows service providers to use other recognized standards/code of practice as safety criteria (European Aviation Safety Agency, 2017).

Next, all the runway incursions and other non-nominal events are fitted in the FAA Risk Matrix. The analysis shows that in the scenario simulated there are 1 High Risk [Red], 4 Medium Risks [Yellow] and 6 Low Risks [Green].

Chapter 10 presents the identification of bottlenecks for multiple remote tower operations. As identified in Chapter 9, the risk associated with multiple remote tower operation is high, so mitigations have to be put in place to ensure the operations are at least as safe as before. The mitigation strategy is focused on lowering the number of High Risks [Red] and Medium Risks [Yellow]. The two bottlenecks are that the ATCO forgets about the pilot Cork Departing Landing_k and gives a line up instruction to the pilot in Cork, and ATCO selection of wrong frequency.

It is important to emphasize that these results are only related to the one scenario being simulated. Therefore, it cannot be excluded that other bottlenecks could be found in other scenarios.

Chapter 11 provides the outcomes of brainstorming activities with subject matter experts (SMEs) for possible improvements for multiple remote tower operations, by addressing the bottlenecks identified in the MC simulation. As part of this, a brainstorming activity was conducted with operational SME. The objective of the brainstorming activity was to present the results of the MC simulation, to analyse and interpret the results using SME input, and to discuss the identified bottlenecks with the aim for the SME to propose possible improvements, if necessary, for multiple remote tower operations.

The SMEs have indicated a list of possible improvements that could be implemented to address the bottlenecks. All the proposed improvements are of course possible. However, before implementation, it has to be verified that these improvements are effective, i.e. that due to implementation no additional hazards are introduced which may pose new risks.

The research has identified 5 non-nominal event types that can pose a risk to the remote tower operations. While two of them, i.e. ATCO selecting the wrong frequency for Shannon and Cork were encountered in the large-scale demonstration, the extend of how much they can affect operations was not known since it only occurred once.

The remaining three types, i.e. runway incursion with potential collision, runway incursion with go-around or instances where the ATCO forgets about the landing aircraft are novel and were discovered with the help of agent-based safety risk modelling and simulation.

This does not only demonstrate the value of this agent-based safety risk modelling and simulation exercise, but also the potential of this model for further research.

Follow up research can focus on extending the agent-based model to include the recommendations from the SMEs. Moreover, it can also be extended to include variations of the MC modelled scenario, such as to include student pilots, callsign similarity etc. or to include additional hazards identified in Chapter 4. The agent-based model can also be used for other airports different than Shannon or Cork.

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Appendices A-E

Please note the following appendices are included in a separate volume:

- Appendix A Shannon Airport
- Appendix B Cork Airport
- Appendix C Notes from the Hazard Identification Human Error Template
- Appendix D List of Hazards from SESAR Safety Assessment
- Appendix E SDCPN Specification of Agent- Based Model for Multiple Remote Tower