Integrated and Joint Optimisation of Runway-Taxiway-Apron Operations on Airport Surface

Suwan Yin

Feb 2022

A thesis submitted as fulfilment of the requirements for the degree of Doctor of Philosophy and the Diploma of Membership of Imperial College London

Centre for Transport Studies
Department of Civil and Environmental Engineering
Imperial College London, United Kingdom

DECLARATION OF ORIGINALITY

I hereby declare that the entire work presented in this thesis has been personally carried out. Where sources of information or the work of others have been used, they are fully cited and referenced and / or appropriate acknowledgement is given.

Signature:

Suwan Yin

COPYRIGHT DECLARATION

ABSTRACT

Airports are the main bottlenecks in the Air Traffic Management (ATM) system. The predicted 84% increase in global air traffic in the next two decades has rendered the improvement of airport operational efficiency a key issue in ATM. Although the operations on runways, taxiways, and aprons are highly interconnected and interdependent, the current practice is not integrated and piecemeal, and overly relies on the experience of air traffic controllers and stand allocators to manage operations, which has resulted in sub-optimal performance of the airport surface in terms of operational efficiency, capacity, and safety.

This thesis proposes a mixed qualitative-quantitative methodology for integrated and joint optimisation of runways, taxiways, and aprons, aiming to improve the efficiency of airport surface operations by integrating the operations of all three resources and optimising their coordination. This is achieved through a two-stage optimisation procedure: (1) the Integrated Apron and Runway Assignment (IARA) model, which optimises the apron and runway allocations for individual aircraft on a pre-tactical level, and (2) the Integrated Dynamic Routing and Off-block (IDRO) model, which generates taxiing routes and off-block timing decisions for aircraft on an operational (real-time) level. This two-stage procedure considers the interdependencies of the operations of different airport resources, detailed network configurations, air traffic flow characteristics, and operational rules and constraints.

The proposed framework is implemented and assessed in a case study at Beijing Capital International Airport. Compared to the current operations, the proposed apron-runway assignment reduces total taxiing distance, average taxiing time, taxiing conflicts, runway queuing time and fuel consumption respectively by 15.5%, 15.28%, 45.1%, [58.7%, 35.3%, 16%] (RWY01, RWY36R, RWY36L) and 6.6%; gated assignment is increased by 11.8%. The operational feasibility of this proposed framework is further validated qualitatively by subject matter experts (SMEs). The potential impact of the integrated apron-runway-taxiway operation is explored with a discussion of its real-world implementation issues and recommendations for industrial and academic practice.

ACKNOWLEDGEMENT

First and foremost, my most sincere gratitude and appreciation goes to my supervisor Professor Washington Yotto Ochieng, who has believed in me from the very first day and given me the opportunity to conduct my PhD research at Imperial College London. In addition, he has given me great instruction and encouragement throughout my four-years of research, and endless support and help in my life. This is endless glory and luck for me being one of his students. I will follow his step in training my students in my future academic career. I also would like to thank Professor Arnab Majumdar and Dr. Panagiotis Angeloudis for their informative and helpful conversations and excellent advice on my thesis at various stages.

My sincere gratitude also goes to Professor Ke Han from Southwest Jiaotong University, who has given me wonderful advice on the technical aspect of my research and journal papers, as well as always readily proofreading my thesis and papers. I deeply appreciate his selfless dedication.

I also would like to thank my previous supervisor at NUAA, Professor Minghua Hu, who are like my family, had trained me for five years before going to Imperial College London to pursue my PhD degree. I would not be the person I am without him. Also, I would like to thank my previous colleagues: Professor Li Xu, Professor Honghai Zhang, Dr. Zheng Zhao, Dr. Lane Yang, for their support, as well as all other colleagues from the National Key Laboratory of Air Traffic Flow Management.

In addition, I would like to thank all my friends and colleagues at Imperial College London, who have offered their help at various stages and aspects of my work. In particular, I thank Dr. Xiang Yun, Dr. Zhongxing Wang, Dr. Junwoo Song, Dr. Yang Yu, Peeranut Jeammaneeporn, Hanyu Meng, as well as all my kind and friendly colleagues from the Imperial ISIM team.

My dearest Gloria Sun, Ru Li, who are like sisters to me, and my little friends, Tingting Zhang, Hongwei Wang, Yucheng Zhang, Dabin Xue, Yihui Bie, Dr. Jianan Yin and Dr. Yuanyuan Ma, Jane Zhang, Linyi Jin, as well as my special friend Dr. Adrian Code, who are like a grandpa to me, I am very blessed to have you all.

ACKNOWLEDGEMENT

Above all, my eternal gratitude goes to all my family members, in particular, my parents: Mr. Wei Yin and Mrs. Sufang Sun, for devoting their lives to me and unconditional love, patience, encouragement and endless support. I understand how tough it is to offer me this opportunity to follow my dream. I am dedicating this work to you. Lastly, I would like to tell my grandpa that I miss you and hope you have peace in paradise.

Suwan YIN

LIST OF CONTENTS

DECLARATION OF ORIGINALITY **2**

COPYRIGHT DECLARATION **3**

ABSTRACT **4**

ACKNOWLEDGEMENT **5**

LIST OF CONTENTS **7**

LIST OF FIGURES **12**

LIST OF TABLES **17**

LIST OF ABBREVIATIONS **19**

CHAPTER 1 INTRODUCTION **24**

1.1. BACKGROUND 24

1.2. AIM AND OBJECTIVES 26

1.3. METHODOLOGIES 28

1.3.1. Qualitative Approach 30

1.3.2. Quantitative Approach 31

1.4. STRUCTURE OF THE THESIS 33

CHAPTER 2 THE AIRPORT SYSTEM **36**

2.1. AIRPORT DEFINITION 36

2.2. AIRPORT COMPONENTS 38

2.2.1. Airport Landside 38

2.2.2. Airport Airside 40

2.3. AIRPORT OPERATION 51

2.3.1. Passenger-centric Operation in the Passenger's Terminal 52

2.3.2. Aircraft-centric Operation on the Airport Surface 53

2.4 STAKEHOLDERS FOR AIRPORT SURFACE OPERATION 55

2.4.1. Airport Authority 55

2.4.2. Ground Handling 57

2.4.3. Airlines 59

2.4.4. Air Traffic Control (ATC) 60

2.4.5. Network Manager 61

2.4.6. Air Navigation Service Providers 62
2.5 KEY PERFORMANCE AREAS AND INDICATORS 64
2.6 SUMMARY 66

CHAPTER 3 STATE-OF-THE-ART OF AIRPORT SURFACE OPERATION 67

3.1. AIRPORT SURFACE MANAGEMENT IN SESAR AND NEXTGEN 67
3.1.1. Arrival Manager 68
3.1.2. Extended Arrival Manager 68
3.1.3. Departure Manager 69
3.1.4. Pre- Departure Manager 69
3.1.5. Surface Manager 69
3.1.6. Advanced-Surface Movement Guidance and Control System 70
3.1.7. Airport Collaborative Decision-Making 71
3.1.8. Surface Collaborative Decision-Making 73
3.1.9. Other Enhanced Airport Operation Solutions in SESAR 75
3.2. OPTIMISATION OF AIRPORT SURFACE OPERATIONS 80
3.2.1. Research Objectives 80
3.2.2. Research Methodology 84
3.2.3. Airport Surface Congestion Management Strategy 87
3.2.4. Resource Utilisation in Isolation 90
3.2.5. Integrated Airport Surface Management 96
3.3. SELECTED CASE STUDY: BEIJING CAPITAL INTERNATIONAL AIRPORT 100
3.3.1. Brief Introduction of PEK Operation 100
3.3.2. PEK Surface Topology 102
3.4. SUMMARY 106

CHAPTER 4 AIRPORT SURFACE TRAFFIC NETWORK MODELLING 108

4.1. TRAFFIC FLOW CHARACTERISTICS AND DYNAMICS 108
4.2. CELL TRANSMISSION MODEL FOR AIRPORT SURFACE TRAFFIC 111
4.2.1. Introduction 111
4.2.2. Fundamental Diagram on Airport surface 111
4.2.3. Details of A-CTM 113
4.3. CELLULAR AUTOMATA FOR AIRPORT SURFACE 122
4.3.1. Introduction 122
4.3.2. A-CA Modelling 123
4.4. SUMMARY 126

CHAPTER 5 INTEGRATED APRON-RUNWAY ASSIGNMENT FOR AIRPORT SURFACE OPERATIONS 127

5.1. PROBLEM SETTING AND ASSUMPTIONS 128
5.2. PROBLEM DEFINITION AND FORMULATION 129
5.3. METHODOLOGICAL FRAMEWORK 133
5.4. APRON AND RUNWAY ASSIGNMENT RULES AND CONSTRAINTS 135
5.4.1. Questionnaire Design 136
5.4.2. Questionnaire and Response 137
5.4.3. Rules and Constraints Used in the Model 141
5.5. PRIORITISATION OF FLIGHT CLUSTERS 142
5.5.1. Questionnaire Design 143
5.5.2. Response of the Questionnaire 144
5.6. JOINT APRON-RUNWAY ASSIGNMENT 147
5.6.1. Lexicographic Approach for Apron Assignment 147
5.6.2. Congestion-aware Runway Assignment 151
5.6.3. Iterative Apron and Runway Assignment Procedure 153
5.6.4. Determination of COBTs Within the A-CA Simulation 155
5.7. EXTERNAL ASSESSMENT AND DISCUSSION OF THE APRON-RUNWAY ASSIGNMENT PROCEDURES 157
5.8. SUMMARY 158

CHAPTER 6 CASE STUDY OF THE JOINT APRON-RUNWAY ASSIGNMENT IN PEK 159

6.1. SCOPE AND PURPOSE OF THE CASE STUDY 159
6.2. FLIGHT INFORMATION AND EXISTING APRON AND RUNWAY ASSIGNMENT 159
6.2.1. Flight data 159
6.2.2. Apron operation 160
6.2.3. Runway Operation 163
6.2.4. Taxiway Operation 166
6.2.5. Operation of Special Aircraft Type 167
6.3. RESULTS OF THE PROPOSED JOINT APRON-RUNWAY ASSIGNMENT 168
6.4. SUMMARY 173

CHAPTER 7 DYNAMIC ROUTE SEARCH AND OFF-BLOCK CONTROL 174

7.1. DEFINITION AND CALCULATION OF DYNAMIC ROUTE IMPEDANCE 174
7.1.1. Free-flow Route Travel Time 175
7.1.2. Interaction Indicator σij 176
7.2. REAL-TIME DYNAMIC ROUTE SEARCH 177

7.2.1. FCFS Approach for Dynamic Route Search 177
7.2.2. Rolling Horizon Approach for Dynamic Route Search..... 179
7.3. INTEGRATED DYNAMIC ROUTING AND OFF-BLOCK CONTROL 182
7.3.1. FCFS Approach for IDRO..... 182
7.3.2. Rolling Horizon Approach for IDRO 183
7.4. PRELIMINARY ASSESSMENT AND DISCUSSION OF THE ROUTING STRATEGIES 185
7.4.1. Examples And Discussion of the Interaction Indicator 185
7.4.2. Examples And Discussion of the Dynamic Route Impedance. 188
7.4.3. FCFS vs Rolling Horizon 190
7.5. SUMMARY 191

CHAPTER 8 VALIDATION OF THE INTEGRATED RUNWAY-TAXIWAY-APRON OPERATIONS 192

8.1. VALIDATION OF THE INTEGRATED AND JOINT SURFACE OPERATION .. 192
8.1.1. Purpose of Validation..... 192
8.1.2. Means of validation 193
8.1.3. Qualitative Assessment of Simulation Results and Implementation Suggestions 194
8.2. DEFINITION AND MEASURING KEY PERFORMANCE INDICATORS 199
8.2.1. Taxi Time 199
8.2.2. Conflicts 200
8.2.3. Taxi Delay..... 204
8.2.4. Runway Queuing and Throughput 204
8.3. A-CA MODEL DEVELOPMENT FOR PEK AIRPORT 206
8.3.1. Airport Surface Network Modelling 206
8.3.2. Apron Modelling 210
8.3.3. Runway Modelling 212
8.3.4. Aircraft Activation..... 218
8.3.5. Empirical Data of PEK Airport 218
8.3.6. Model Calibration and Verification 221
8.4. RESULTS OF INTEGRATED APRON-RUNWAY ASSIGNMENT 225
8.4.1. Results Based on Key Performance Indicators 225
8.4.2. Determination of Calculated Off-block Times 229
8.5. RESULTS OF IDRO OPTIMISATION 230
8.5.1. Dynamic Route Search 230
8.5.2. Integrated Dynamic Routing and Off-block (IDRO) optimisation 244
8.6. JOINT IARA-IDRO 252
8.7. DISCUSSION..... 253

8.8. SUMMARY 255

CHAPTER 9 RECOMMENDATIONS FOR IMPLEMENTATION 256

9.1. RESEARCH OUTPUT AND FINDINGS 256

9.2. IMPLEMENTATION CONSIDERATION 259

9.3. SUMMARY 260

CHAPTER 10 CONCLUSION AND FUTURE WORK 261

10.1 COMPLETION OF RESEARCH OBJECTIVES 261

10.2 QUALITATIVE AND QUANTITATIVE ASSESSMENTS 264

10.3 FUTURE RESEARCH DIRECTIONS 265

REFERENCES 266

APPENDICES 287

APPENDIX 1. DEFINITION OF KEY PERFORMANCE AREAS BY ICAO 287

APPENDIX 2. EXAMPLES OF REAL-WORLD DATA AT PEK 290

APPENDIX 3. EXAMPLES OF AIRCRAFT BASIC INFORMATION 291

APPENDIX 4. IATA CODES FOR AIRPORTS AND AIRLINES 292

LIST OF FIGURES

Figure 1.1. Overall structure of the thesis and corresponding objectives..... 35
Figure 2.1. Physical structure and functions of an airport..... 39
Figure 2.2. Example of a physical structure of an International Airport Terminal 40
Figure 2.3. Passenger terminal apron structure concepts (adopted from ICAO (2005b))..... 44
Figure 2.4. Open V with dependent operations away from the intersection; (b) Open V with dependent operations towards the intersection; (c) Intersecting runways with dependent operations away from the cross point; (d) Intersecting runways with dependent operations.. 47
Figure 2.5. Examples of the classification of runway configurations around the globe (Yin, 2016)..... 49
Figure 2.6. Apron taxiway, stand taxi lane and lead-in lines (adopted from ICAO (2005b)). 51
Figure 2.7. (a) Departure process of passengers; (b) Arrival process of passengers. The process circled in the box only for international flights 52
Figure 2.8. Diagrammatic overview of airport operation process (EUROCONTROL, 2005) 55
Figure 2.9. Stakeholders on the airport surface operation (adopted from EUROCONTROL, 2015)..... 63
Figure 3.1. The A-CDM Milestones（EUROCONTROL, 2015） 72
Figure 3.2. The A-CDM stakeholders and objectives (EUROCONTROL, 2015)..... 73
Figure 3.3. Collaboration of AMAN, DMAN, SMAN within A-CDM..... 75
Figure 3.4. Operation volume of PEK from 2010 to 2019 101
Figure 3.5. Hourly movements at PEK on 14/09/2017 101
Figure 3.6. Aerial view of PEK airport (adopted from Google Map) 103
Figure 3.7. Schematic diagram of three runways at PEK..... 104
Figure 4.1. Schematic diagram of airport surface network (Yang et al., 2017) 109
Figure 4.2. Empirical flow-density-speed relationship of traffic flow at apron area and taxiway (Yang et al., 2017) 110
Figure 4.3. Density-flow relationship of traffic flow at apron or taxiway links. Left: Trapezoidal (apron traffic); right: Triangular (taxiway traffic)..... 112

LIST OF FIGURES

Figure 4.4. Merge, diverge, and crossover junctions. No turning is allowed at the crossover junction 115
Figure 4.5. Cell representation of the runway queuing area 119
Figure 4.6. Left: the cell representation of runway network. Right: the fundamental diagram of the runway cell 120
Figure 4.7. Cell representation of the apron area 121
Figure 4.8. State transitions at a node (adopted from Sanchez (2019)) 125
Figure 5.1. Overall methodology of the proposed IARA 133
Figure 5.2. Flow chart of the proposed joint apron-runway assignment 135
Figure 5.3. Empirical distributions of $\boldsymbol{\varepsilon Arr}$ and $\boldsymbol{\varepsilon Dep}$ 149
Figure 6.1. Airport surface network topology 161
Figure 6.2. Relative positions of departure fixes (operation in north) 165
Figure 6.3. Single direction of taxi flow instruction in north direction (adopted from Operational Manual of PEK) 167
Figure 6.4. Flight characteristics (top) and number of stands in each apron (bottom) 168
Figure 6.5. O-D distribution before (left column) and after (right column) apron-runway assignment ($\boldsymbol{\delta 1Arr = \delta 2Dep = 0}$). Each row shows the number of flights in each apron that uses Runway01 (top), Runway36R (middle) and Runway36L (bottom), respectively. 170
Figure 6.6. O-D distribution results of the proposed apron-runway assignment, left column: $\boldsymbol{\delta 1Arr = 0, \delta 2Dep = 0}$; right column: $\boldsymbol{\delta 1Arr = -20, \delta 2Dep = 40}$. Each row shows the number of flights in each apron that uses Runway01 (top), Runway36R (middle) and Runway36L (bottom), respectively. 171
Figure 7.1. Network representation of turning curves 175
Figure 7.2. Flow chart of the FCFS dynamic route search procedure 178
Figure 7.3. Flow chart of the rolling-horizon dynamic route search procedure 180
Figure 7.4. Node arrival times, $\boldsymbol{t1 < t2 < t3 < t4 < t5 < t6}$. 185
Figure 7.5. Node arrival times, $\boldsymbol{t1 < t2 < t3 < t4 < t5 < t6}$. 187
Figure 7.6. Example of the dynamic route impedance. 189
Figure 7.7. Example of the dynamic route impedance (with a later start time). 189
Figure 8.1. Flow Chart of the validation process 193

LIST OF FIGURES

Figure 8.2. Examples of special apron structure (Yin, 2018) 201
Figure 8.3. Examples of conflicts within aprons (Yin, 2018) 201
Figure 8.4. Examples of taxiway conflicts (Yin, 2012) 202
Figure 8.5. Examples of runway conflicts: (a)vertical runway crossing; (b)crossing via runway; (c) runway end-slip crossing (Yin, 2012) 203
Figure 8.6. Flowchart of the A-CA modelling 207
Figure 8.7. Example of directed links 208
Figure 8.8. Airport surface modelling at PEK 216
Figure 8.9. Scheduled flight plan on 14/09/2017 at PEK 220
Figure 8.10. Cumulative runway throughput: three runways combined (top); each runway (bottom), on 14th Sep. 223
Figure 8.11. Cumulative runway throughput: three runways combined (top); each runway (bottom), on 17th Sep. 224
Figure 8.12. Runway throughputs (incl. arrivals and departures) before and after the apron-runway assignment 226
Figure 8.13. Box plots of maximum runway queuing and mean queuing times from 10 independent ACA simulation runs. 228
Figure 8.14. Conflict comparison before (left) and after (right) assignment 229
Figure 8.15. Convergence of the iterative apron-runway assignment (left) and COBT determination (right) 230
Figure 8.16. Boxplots (over 10 simulation runs) of average taxiing time for all flights. 232
Figure 8.17. Boxplots (over 10 simulation runs) of average taxiing time for arrival flights. 233
Figure 8.18. Boxplots (over 10 simulation runs) of average taxiing time for departure flights. 233
Figure 8.19. Boxplots (over 10 simulation runs) of average delay for all flights. 234
Figure 8.20. Boxplots (over 10 simulation runs) of total number of conflicts on the airport surface 234
Figure 8.21. Histogram of relative reduction of route impedance for each aircraft 236
Figure 8.22. Histogram of relative reduction of route impedance for arrival aircraft 236
Figure 8.23. Histogram of relative reduction of route impedance for departure aircraft 236

Figure 8.24. Relative reduction of route impedance for all aircraft by time of their entrance into the surface network 237
Figure 8.25. Default and alternative routes for two O-D pairs: (Apron 4, RWY01), (Apron 24, RWY36R) 238
Figure 8.26. Relative reduction of route impedance (over the default route) by dynamic route search for all aircraft between O-D (Apron 4, RWY01) 239
Figure 8.27. Relative reduction of route impedance (over the default route) by dynamic route search for all aircraft between O-D (Apron 24, RWY36R) 239
Figure 8.28. Default and alternative routes for two O-D pairs: (Apron 4, RWY36R), (Apron 10, RWY36L) 240
Figure 8.29. Relative reduction of route impedance (over the default route) by dynamic route search for all aircraft between O-D (Apron 4, RWY36R) 241
Figure 8.30. Relative reduction of route impedance (over the default route) by dynamic route search for all aircraft between O-D (Apron 10, RWY36L) 241
Figure 8.31. Default route choices: Average number of conflicts (over 10 independent simulation runs) at each node 242
Figure 8.32. Dynamic route search: Average number of conflicts (over 10 independent simulation runs) at each node 243
Figure 8.33. Spatial distribution of node conflicts (the numerical scale indicates total number of conflicts occurred during the one-day operational horizon) with default route choices... 243
Figure 8.34. Spatial distribution of node conflicts (the numerical scale indicates total number of conflicts occurred during the one-day operational horizon) with the dynamic route search algorithm 244
Figure 8.35. Histogram of relative reduction of route impedance for departure aircraft 246
Figure 8.36. Relative reduction of route impedance for all departing aircraft by time of their entrance into the surface network 247
Figure 8.37. Distribution of aprons and runways. For departures, the destinations are RWY01, RWY36R and RWY 36L. 248
Figure 8.38. Dynamic route search: Average number of conflicts (over 10 independent simulation runs) at each node 249

Figure 8.39. Integrated dynamic route and off-block optimisation: Average number of conflicts (over 10 independent simulation runs) at each node 250
Figure 8.40. Spatial distribution of node conflicts (the numerical scale indicates total number of conflicts occurred during the one-day operational horizon) with the dynamic route search algorithm..... 251
Figure 8.41. Spatial distribution of node conflicts (the numerical scale indicates total number of conflicts occurred during the one-day operational horizon) with the integrated dynamic routing and off-block optimisation. 251

LIST OF TABLES

Table 1.1. Methodological approach and outcomes of each chapter of the thesis. 29
Table 2.1. IATA-IDRO operational objectives, and corresponding KPIs in terms of the main KPAs..... 65
Table 3.1. Comparison of the operational concepts 74
Table 3.2. Basic information of runways at PEK airport 103
Table 3.3. Airline distribution at PEK airport (adopted from BCIA (2017) 105
Table 4.1. Spatial headway matrix in CAN..... 114
Table 5.1. Flight clusters (arranged in decreasing order of priority) and their defining attributes 146
Table 6.1. Examples of apron assignment preference 162
Table 6.2. MTAT for different aircraft type in PEK 163
Table 6.3. Runway entrance and exit Points 164
Table 6.4. Examples of runway preferences for some airlines..... 166
Table 6.5. Comparison of apron-runway assignment results with different buffers 172
Table 6.6. Taxiing distance reduction (compared to the current operation) by different fight attributes. The buffers are $\delta 1Arr = -20, \delta 2Dep = 40$ 172
Table 8.1. Speeds of the model. (Units: cells/unit time) 210
Table 8.2. Basic parameters of the aprons..... 211
Table 8.3. Minimum wake turbulence separation rule for consecutive departures (unit: seconds) 214
Table 8.4. Minimum wake turbulence separation rule for consecutive arrivals (unit: kilometers) 215
Table 8.5. Exit probability for each aircraft type on each runway 217
Table 8.6. Runway entrance and displaced threshold point at PEK..... 217
Table 8.7. Error summary for average taxiing time for the A-CA model (14th Sep) 222
Table 8.8. Error summary for average taxiing time for the A-CA model (17th Sep) 222
Table 8.9. Key performance indicators from ACA simulation based on the current and new apron-runway assignment..... 226

Table 8.10. Reduction of fuel consumption and emissions from the new apron-runway assignment ($\delta 1Arr = -20, \delta 2Dep = 40$)..... 228
Table 8.11. Comparison of default routing and dynamic route search in terms of KPIs (over 10 simulation runs). 231
Table 8.12. Comparison of default route, dynamic route search, and IDRO. 245
Table 8.13. Top 10 O-Ds with the most average impedance reduction. 248
Table 8.14. Key performance indicators from ACA simulation based on the current and new proposed integrated and joint optimisation research 253
Table 9.1. Required data and airport information 258

LIST OF ABBREVIATIONS

2D	Two dimensional
3D	Three dimensional
4D	Four dimensional
A-CA	Cellular Automata on Airport surface
ACARS	Airborne Collision Avoidance System
A-CDM	Airport Collaborative Decision Making
ACI	Airports Council International
A-CTM	Cell Transmission Model for Airport surface traffic
ADS-B	Automatic Dependent Surveillance- Broadcast
ADS-C	Automatic Dependent Surveillance- Contract
AHM	Airport Handling Manual
AIP	Aeronautical Information Publication
AIS	Aeronautical Information Services
AMAN	Arrival Management
ANS	Air Navigation System
ANSPs	Air Navigation Service Providers
AOCC	Airport Operation Control Centre
AOP	Airport Operation Plan
APOC	Airport Operation Centre
ASBU	Aviation System Block Upgrades
ASCM	Airport Surface Congestion Management
A-SMGCS	Advanced Surface Movement Guidance and Control System
ASH	Average Spatial Headway
ATA	Actual Time of Arrival
ATC	Air Traffic Control
ATCO	Air Traffic Control Operator
ATFCM	Air Traffic Flow and Capacity Management
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATOT	Actual Take-off Time

LIST OF ABBREVIATIONS

ATS	Automatic Train Supervision
ATSU	Air Traffic Service Unit
AUP	Airspace User Plan
A-VDGS	Advanced-Visual Docking Guidance System
BA	British Airways
CAA	Civil Aviation Authority
CAAC	Civil Aviation Administration of China
CAST	Commercial Aviation Safety Team
CDQM	Collaborative Departure Queue Management
CFMU	Central Flow Management Unit
CFL	Courant-Friedrichs-Lewy
CNS	Communication, Navigation and Surveillance
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COBT	Calculated Off-Block Time
ConOps	Concept of Operations
CPDLC	Controller-Polit Datalink Communications
CPP	Clique Partition Problem
CTM	Cell Transmission Model
CTOT	Calculated Take-Off Time
DCS	Departure Control System
DMAN	Departure Management
DME	Distance Measuring Equipment
EACCC	European Aviation Crisis Coordination Cell
E-AMAN	Extended Arrival Manager
EASA	European Aviation Safety Agency
EC	European Commission
ELDT	Estimated Landing Time
EOBT	Earliest Off Block Time
ETA	Estimated Time of Arrival
ETD	Estimated Time of Departure

ETL	Electronic Ticket List
EVS	Enhanced Vision System
EU	European Union
EUROCONTROL	European Organisation for the Safety of Air Navigation
EVS	Enhanced Vision System
FAA	Federal Aviation Administration
FD	Fundamental Diagram
FFC	Future Flights Central
FMS	Flight Management System
FOD	Foreign Object Debris
GA	Genetic Algorithm
GBAS	Ground Based Augmentation System
GMC	Ground Management Controller
GNSS	Global Navigation Satellite System
GSP	Ground Service Provider
HMI	Human Machine Interface
IARA	Integrated Apron and Runway Assignment
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ID	Identity Document
IDRO	Integrated Dynamic Route and Off-block control
IGOM	IATA Ground Operation Manual
ILP	Integer Linear Programming
ILS	Instrument Landing System
IP	Integer Programming
KPA	Key Performance Areas
KPI	Key Performance Indicators
LP	Linear Programming
LWR	Lighthill-Whitham-Richards
MATLAB	Matrix & Laboratory
MFD	Macroscopic Fundamental Diagram

MET	Meteorological
MILP	Mixed Integer Linear Programming
MTAT	Minimum Turn-around Time
MTOW	Maximum Take-Off Weights
NAA	National Aviation Authorities
NASA	National Aeronautics and Space Administration
NextGen	Next Generation
NLR	National Airspace Laboratory
NNEW	NextGen Network Enabled Weather
NOP	Network Operation Plan
NVS	NAS Voice Switch
NM	Network Manager
OCC	Operational Control Centre
PBN	Performance-Based Navigation
PCP	Pilot Common Project
PPE	Personal Protective Equipment
PRC	Performance Review Commission
RAGA	Robust Airport Gate Assignment
RECAT	Re-categorise
RELs	Runway Entrance Lights
RILs	Runway Intersection Lights
RVT	Remote and Visual Tower
SAR	Search And Rescue
RWSL	Runway Status Lights
SARDA	Spot and Runway Departure Advisor
SBAS	Satellite-Based Augmentation System
S-CDM	Surface Collaborative Decision Making
SES	Single European System
SESAR	Single European Sky Air Traffic Management Research
SET	Single-engine Taxi
SIDs	Standard Instrument Departures

SMAN	Surface Management
STA	Scheduled Time of Arrival
STARs	Standard Instrument Arrivals
STD	Scheduled Time of Departure
SVS	Synthetic Vision Systems
SMEs	Subject Matter Experts
SWIM	System-wide Information Management
TAM	Total Airport Management
TBS	Time-Based Separation
TC	Terminal Controllers
TCL	Taxiway Centreline Lights
THLs	Take-off Hold Lights
TLDT	Target Landing Time
TMA	Terminal Manoeuvring Area
TMAT	Target Movement Area Time
TMIs	Traffic Management Initiatives
TOBT	Target Off-block Time
TSAT	Target Start-Up Time
TTG	Time To Gain
TTL	Time To Lose
TTOT	Target Take-Off Time
TWR	Tower Controller
UHF	Ultra-High Frequency
VHF	Very High Frequency
VTT	Variable Taxiing Time
WDS	Weather Dependent Separations

CHAPTER 1 INTRODUCTION

1.1. BACKGROUND

The Single European Sky Air Traffic Management Research (SESAR) programme (EUROCONTROL, 2018) and Next Generation Air Transportation System (NextGen) plan (FAA, 2016) aim to increase air traffic network throughput to accommodate a predicted 50% increase in air traffic volume by 2035. Such a rapid growth will put pressure on airport surface management, creating bottlenecks in the Air Traffic Management (ATM) system. Furthermore, due to the high demand for flights, more than 30 airports will be congested by 2035, operating at over 80% of their capacity for more than three hours per day (EUROCONTROL, 2013c). Compared to Europe, the level of congestion is higher in China. In 2017, more than 20 airports were already operating at 90% of their capacity for more than 15 hours of the day during the peak months of July to September (CAAC, 2017). This has contributed directly to large-scale congestion and local delays in the air traffic network in China.

There are two main ways to mitigate operational congestion in airports: improved resource utilisation (i.e. of runways, taxiways, and aprons) and physical expansion. Airport surface consists of three infrastructure systems: runways, taxiways, and aprons. Airport capacity may be expanded by investing in infrastructure, such as adding new resources, building additional runways and stands, and rapid taxiway exits. A significant shortcoming of physical expansion is cost, long acquisition times and the potential to increase airport complexity and relevant airspace configurations with the real risk of offsetting the capacity-related benefits from the investment. Therefore, this thesis focuses on improved utilisation to optimise airport surface operations, which in addition to increasing capacity, should also be a pre-requisite for any consideration of physical expansion.

To improve airport surface operation, significant research effort has been dedicated to introducing new operational concepts, procedures, and decision support tools by SESAR and NextGen, e.g. Airport Collaborative Decision Making (A-CDM), Advanced Surface

Movement Guidance and Control System (A-SMGCS), Spot and Runway Departure Advisor (SARDA), Pushback Control, Collaborative and Departure Queue Management (CDQM). However, despite these efforts and systems - according to the latest report on "Comparison of ATM-related performance in US/Europe" (PRC, 2018) - in 2017, 86% of the total delay-generating Traffic Management Initiatives (TMIs) in the US are attributed to airports, while this number is 35% in Europe. In total, this resulted in 14.4 million minutes of reportable delays in the US and 5.1 million minutes in Europe. Furthermore, airports account for 83% of the reportable ATFM delays in the U.S, and 43% in Europe. Congestion at airports also leads to additional fuel burn and emissions (e.g., NOx, CO). In 2017, the average excess fuel burns during the taxi-out phase were 3kg and 13kg more than those in 2015, in the EU and US respectively (PRC, 2015&2018; EUROCONTROL, 2014c).

On the other hand, many academic studies have been undertaken with the aim of improving operational efficiency by increasing the utilisation of operational resources (i.e. runway, taxiway, apron) on the airport surface. However, existing research and practice to date have focused either on optimising each resource in isolation (i.e. runway management, taxiing planning, gate assignment), or partial integration of components (e.g. integrated taxiing scheduling and runway sequencing). Very little effort has been dedicated to the joint optimisation of all resources (in particular, joint assignment of gate and runway), despite the fact that all three resources are interconnected and interdependent in terms of both physical structures and operational processes. This lack of integration results in sub-optimality and inefficiency. Moreover, a major weakness in these studies is that they are all constrained within a network configuration with fixed and known origin–destination of aircraft movement. The possibility of reconfiguring the spatial distribution of origins (i.e. aprons for departures or runways for arrivals) and destinations (i.e. aprons for arrivals or runways for departures) has not yet been considered, due to the high level of complexity resulting from the range of operational constraints and stakeholders (Atkin et al., 2010).

In light of this, a holistic (integrated) framework for airport surface operation is required to fully use the resources in a systematic and harmonised manner, in a way that improve

operational efficiency by delivering operational improvement that increases traffic throughput and reduces operational congestion, while providing environmental benefits and preserving safety. To the best of the author's knowledge, this is the first research that develops a framework capable of integrated optimisation of runway, taxiway, and apron operations, contrast to existing operation or studies that focus on separate management or sequential optimisation.

1.2. AIM AND OBJECTIVES

Motivated by the current limitations referred to the background (Section 1.1), this thesis aims to design a framework for the integrated and joint optimisation of the runway-taxiway-apron system, by considering the interdependencies of their operations, detailed network configuration, flow dynamics, and the operational constraints and preferences. The main goal is to improve the airport operational efficiency in terms of Key Performance Indicators (KPIs) including taxiing distance, taxiing time, taxiing conflicts, taxiing delay, and runway queuing, with indirect benefits to environmental KPIs such as emissions and fuel consumption. This is accomplished by considering the following objectives.

1) Review relevant literature to gain critical understandings of: (a) research methodology related to the optimisation of airport operations; (b) the main hurdles to airport capacity expansion and operational improvement from methodological and regulatory perspectives; and (c) administrative and technological constraints for the proposed integrated apron-taxiway-runway optimisation (see Chapters 2 and 3). As part of the mixed methodology (see Section 1.3 for details), this literature review is completed in part using a qualitative approach (including interviews with SMEs company with site visit). The review of current regulations, design and management practice has led to the derivation of a set of design objectives, requirements, and constraints.

2) Set up and calibrate a microscopic simulation model for airport surface movement based on the Cellular Automata model for the Airport surface (A-CA). Again, as part of the mixed methodology, this calibrated model serves as the main simulation platform to quantitatively assess the proposed optimisation solutions and evaluate its effectiveness by computing relevant Key Performance Indicators (KPIs) (see Sections 4.3 and 8.3). To validate the model, its input parameters and simulation outputs under various scenarios were checked by the SMEs from PEK AOC. The A-CA is also embedded in the dynamic route search and off-block algorithms to dynamically generate routes and off-block times, by simulating the real-time operational environment (see Sections 7.2 & 7.3).

3) Perform integrated apron-runway (origin-destination) assignment (IARA) on a pre-tactical level, while considering airport operational constraints as well as runway and apron assignment rules and preferences. This is achieved with a mixed qualitative-quantitative approach where apron and runway assignment rules and constraints, as well as cluster ranking were first obtained from interviews with SMEs (Section 5.4) and questionnaire survey (Section 5.5), which serve as the guidance for designing optimisation procedures that are quantitative in nature (Section 5.6)

4) Building on the IARA solution in Objective 3, develop dynamic route search and integrated dynamic routing and off-block (IDRO) optimisation algorithms in a real-time decision environment, with empirical data and operational rules as inputs. This is done via a quantitative approach based on the novel notion of dynamic route impedance (see Chapter 7)

5) Validate and assess the operational feasibility and effectiveness of the proposed joint IARA-IDRO optimisation framework, based on a case study in PEK using real-world data. The validation test concerns both quantitative evaluation in terms of a range of KPIs, and qualitative assessment on its operational viability and potential for field implementation (Chapter 8).

6) Based on the qualitative and quantitative assessments of the results, make recommendations for industrial and academic practice. In particular, consider how the proposed research framework and outcome can be adopted and adjusted to deal with the real-world operational environment and operational diversities across different geographical locations, and how the planning and design of airports can be informed by the research outcome to improve their efficiency and safety performances (Chapter 9).

1.3. METHODOLOGIES

To achieve the main goal set forth in this thesis with a balanced consideration of the effectiveness of the optimisation and feasibility in real-world implementation, a mixed quantitative-qualitative methodology (Cohen and Morrison, 2002; Shorten and Smith, 2017; Sidiropoulos, 2016) is proposed. The mixed methodology, on the one hand, makes sure that the modelling and optimisation of airport surface traffic are properly informed by the operational rules of the airport and the user preferences of key stakeholders, while on the other hand generating test scenarios and quantitative results that can be assessed by subject matter experts in terms of the operational feasibility of the proposed designs and their potential impact to airport operations. The mixed methodological approach and corresponding outcomes of each chapter of the thesis are summarised in Table 1.1. The METHODOLOGY column highlights the qualitative, quantitative, or mixed nature of the methods involved.

Table 1.1. Methodological approach and outcomes of each chapter of the thesis.

CHAPTER	METHODOLOGY	OUTCOMES
1. Introduction	Background of the problem	Aims and objectives of the thesis
2. The airport system	Critical review of the airport system	Integrated optimisation is a potentially effective measure to maximise the utilisation of network capacity and to improve operational efficiency
3. State-of-the-art of airport surface operations	Critical understandings of airport surface optimisation from both industrial (SESAR and NextGen) and academic perspectives	Identification of research gap: lack of integrated optimisation of surface operation. Consideration and rationale for choosing PEK for the case study
4. Airport surface traffic network modelling	**Quantitative:** Mathematical modelling	Airport surface traffic flow characteristics and modelling techniques
5. IARA framework for airport surface	**Mixed:** Development of a mathematical model and optimisation framework based on interviews with SMEs on the key attributions and their rankings in the context of apron and runway assignment.	A framework for optimal apron and runway allocation for all flights on a pre-tactical level.
6. Validation of the proposed IARA framework	**Mixed:** mathematical optimisation models and interviews with SMEs	Performance validation: KPIs in terms of taxiing distance, gated assignment, and conflicts
7. IDRO framework	**Quantitative:** Development of a mathematical model and optimisation procedure	Real-time least-impeded routing and off-block time for both departures and arrivals
8. Validation of the IARA-IDRO operations	**Mixed:** Implementation of ACA simulation guided by the operational rules and constraints of PEK, and interviews with SMEs regarding the validity of the results	Performance evaluation of the joint IARA-IDRO optimisation in terms of several KPIs and qualitative assessment of their operational feasibility and potential applicability.
9. Implementation issues and application considerations	Findings and discussion of the impact	Framework implementation and potential impact
10. Conclusion and future work	Summary and future work	Completion of the research objectives, and guidelines for future work

1.3.1. Qualitative Approach

While a literature review provides an initial understanding of the proposed work and its context, Subject Matter Experts' opinions are also required to ensure a correct understanding of the airport surface operations considering the complexity and numerous intricacies of airport surface operations. This is required to confirm the rationality of the proposed concept, and collect qualitative data (rules and constraints of apron and runway, cluster attributes and ranking), as well as to validate the findings and provide suggestions for field implementation, in different stages of the research. To this end, a series of semi-structured interviews and questionnaire surveys were arranged with SMEs representing several stakeholders related to the various processes of this research (Savin-Baden and Howell-Major, 2013).

The first round of interviews was facilitated by PEK Airport (the airport selected for the case study), accompanied by site visits. By means of a series of face-to-face interviews with SMEs representing the following stakeholders: Airport (in terms of AOC duty manager, airside resource manager, stand planner), ATC (Beijing tower controller), Airline (Air China Airlines, Hainan Airlines). These interviews provided 1) an understanding of the current PEK surface operation characteristics and an initial discussion of the feasibility of the proposed integrated and joint optimisation; 2) a collection of operation-related documents from airports in terms of rules, constraints, and preferences of the runway, taxiway, and apron operations, one-year real-world historical data, airport topology (see Section 6.2); 3) rules, constraints, and preferences that should be considered while assigning runway and apron allocations (see Section 5.4).

The second round of quantitative research was performed via a questionnaire survey (see Section 5.5). Five interviewees who attended the first round, with 11 years of working experience on average and specialising in apron assignment and airside operations, were selected for the second round. This questionnaire survey was conducted to gain the result of the priority ranking of the 20 cluster groups to be considered later in the mathematical optimisation model. This survey consists of two procedures. First of all, five SMEs answered the questionnaires independently. Secondly, with a balanced consideration of their responses,

the ranking of the 20 clusters (see Section 5.5.2) was agreed by all the SMEs during a group discussion.

The third round of qualitative assessment was conducted to validate the effectiveness of the proposed integrated work and to provide suggestions regarding the potential applications and the future implementation. This was achieved by interviewing *SMEs and representatives of different stakeholders* in an online meeting (see Section 8.1.3). In this process, three aspects were considered. The first aspect was the validation of the simulation setup for the Base Case and the Test Case models. The second aspect is the validation of the proposed optimisation framework at different operational levels. The third aspect is to gain insights into the operational feasibility of the proposed joint optimisation, and its potential for field implementation in the future. A series of semi-structured interviews were arranged with representatives of different stakeholders.

1.3.2. Quantitative Approach

Following the development of the concept of operations, a series of mathematical models were employed in each model stage described in Chapters 5 and 7, respectively, to quantify the benefit of the proposed research, as well as a case study and a simulation model described in Chapters 6 and 8, respectively, to assess the validity and effectiveness of the proposed IARA-IDRO framework on the basis of KPIs as described in Section 2.5.

Following the development of the concept of operations, a product of the identification of the surface operations, is the development of a series of mathematical models described in Chapter 5 and Chapter 7.

Chapter 5 proposes a novel iterative apron-runway assignment method with embedded lexicographic and congestion-aware optimisation techniques. This is achieved by considering various physical and operational constraints in terms of the runway and apron assignment rule, airport and airline preferences, TMA constraints, surface network topology, taxiing dynamics

and so on. The proposed Integrated Apron-Runway Assignment (IARA) aims to achieve the **optimal spatial-temporal distribution** of airside traffic demands, in a way that significantly reduces required taxiing distances, with the added benefits of shorter taxiing time, fewer conflicts, reduced runway queuing, and increased gate assignments. Moreover, to handle temporal uncertainties, a data-driven robust approach was embedded to absorb uncertainties at the pre-tactical level.

In Chapter 7, an Integrated Dynamic Routing and Off-block (IDRO) optimisation approach for real-time airport surface operations is proposed. This was achieved based on a novel notion of dynamic route impedance, which is adapted from road traffic theory and extended to encapsulate free flow taxiing time, turning curves, and potential aircraft conflicts along the route. In particular, when a departing aircraft is pulled from the stand or an arriving aircraft exits the runway, it is dynamically assigned an optimal path by an algorithm, which takes it to the least-impeded route for taxiing to its destination.

In chapter 8, an airport automata (A-CA) simulator is employed for the quantitative evaluation of the proposed concept of operations in terms of KPIs (see Section 2.5). The following features are notable about the simulation model:

- **Realistic modelling of operations:** The simulator attempts to simulate airport surface operations as closely as possible to reality, including the unique characteristics of dynamic traffic flow on the airport surface, in terms of an apron, taxiway, and runway movement, respectively, and the conflict resolution regulation, conflict hot spots, speed regulations, runway ramp assignment, and other operational rules and constraints.
- **Computation time is necessary for supporting real-time decision assistance:** This A-CA model (Objective 2) serves as the main platform for simulating current operations as well as validating the proposed optimisation solutions. A simulation can only simulate as closely as possible to the reality, it cannot replay 100% of a historical operation. Moreover, due to the presence of uncertainty in the model, such as speed randomization, runway exit

selection, a batch of random simulations should be performed and an average of 10 independent runs for one day of empirical data were adopted as simulation results.

- **Accurate simulation inputs are crucial to this process and for this there is a need for assistance from SMEs:** To ensure the validity of the A-CA modelling and results, real-world operational data were used as input to the model. The benefit of using real-world data was twofold; firstly, it allowed for modelling realistic surface operations within the A-CA model, and secondly, it enabled a direct comparison between the A-CA results and the actual operations, thus providing additional insurance for the quality of the developed A-CA model. The results were then validated by the SMEs from PEK AOC by both checking the key input parameters and the simulation results.

1.4. STRUCTURE OF THE THESIS

This thesis is organised in ten chapters as follows.

Chapter 2 provides a description of the airport system, by elaborating the airport definition and its importance in the current ATM system, airport components, airport operations from the perspectives of both passengers and aircraft, key stakeholders of aircraft operation on the airport surface, as well as KPAs and corresponding KPIs.

On the basis of the airport surface operation process, **Chapter 3** presents the state-of-the-art for airport surface operation. This includes operational concepts, new technologies, and procedures proposed by SESAR and NextGen, as well as a literature review of previous academic studies related to an individual or partially integrated optimisation of the runway, taxiway, and apron operations. Based on the state-of-the-art, the importance of integrating the framework of runway-taxiway-apron operations, which is a key element envisaged by both NextGen and SESAR, is highlighted. In addition, an introduction to the PEK is presented, this

is later used as the main case study to validate the effectiveness of the proposed framework in this research (Chapter 6 and Chapter 8).

To model the airport surface network, **Chapter 4** studies traffic dynamics on the airport surface network. This is achieved by describing the traffic flow characteristics and dynamics, followed by two detailed network models for the airport surface, namely the mesoscopic Cell Transmission Model (CTM) and the microscopic Cellular Automata model (CA).

Chapter 5 presents the first stage of the integrated framework for runway-taxiway-apron operations. This is achieved by first presenting the framework for integrated apron-runway assignment (IARA) for aircraft movement on the surface network on a pre-tactical level, while considering airport operational constraints as well as runway and apron assignment rules and preferences. This is achieved by devising a series of mathematical algorithms and an optimisation framework based on interviews with SMEs on the key attributes and their rankings in the context of apron and runway assignment.

To assess the validity and effectiveness of the proposed IARA framework presented in Chapter 5, a case study at PEK using real-world data is performed in **Chapter 6**. This is done by instantiating the network model, assignment rules, operational constraints and preferences based on actual data in PEK. Detailed results and analyses are included.

Chapter 7 develops the second stage of the integrated optimisation framework. In this chapter, dynamic path search (DRS), integrated dynamic routing and off-block (IDRO) optimisation for departures are developed to further optimise the taxiing process based on the O-D assignment studied in Chapter 6. This is done by proposing and implementing the concept of dynamic path impedance and developing optimisation algorithms based on the first-come-first-served or rolling-horizon principles.

Chapter 8 presents a comprehensive validation process for the proposed integrated framework, including IARA and IDRO optimisation procedures. This is done by first introducing the KPIs used for quantitative assessment, and then validating the results of the A-CA simulation model.

Extensive simulation tests and sensitivity analyses are performed to evaluate the effectiveness and robustness of the optimisation procedures. Furthermore, a series of qualitative validations are conducted based on interviews with SMEs, in order to gain insights into the operational feasibility of the proposed joint optimisation, and potential issues for field implementation.

Chapter 9 summarises the main findings of this thesis and lays down a pathway forward for implementation of the proposed framework.

Chapter 10 draws conclusions from this research and identifies caveats and guidelines for future work.

Figure 1.1 shows the overall structure of the thesis by assigning the six objectives to different chapters and indicating their interdependencies.

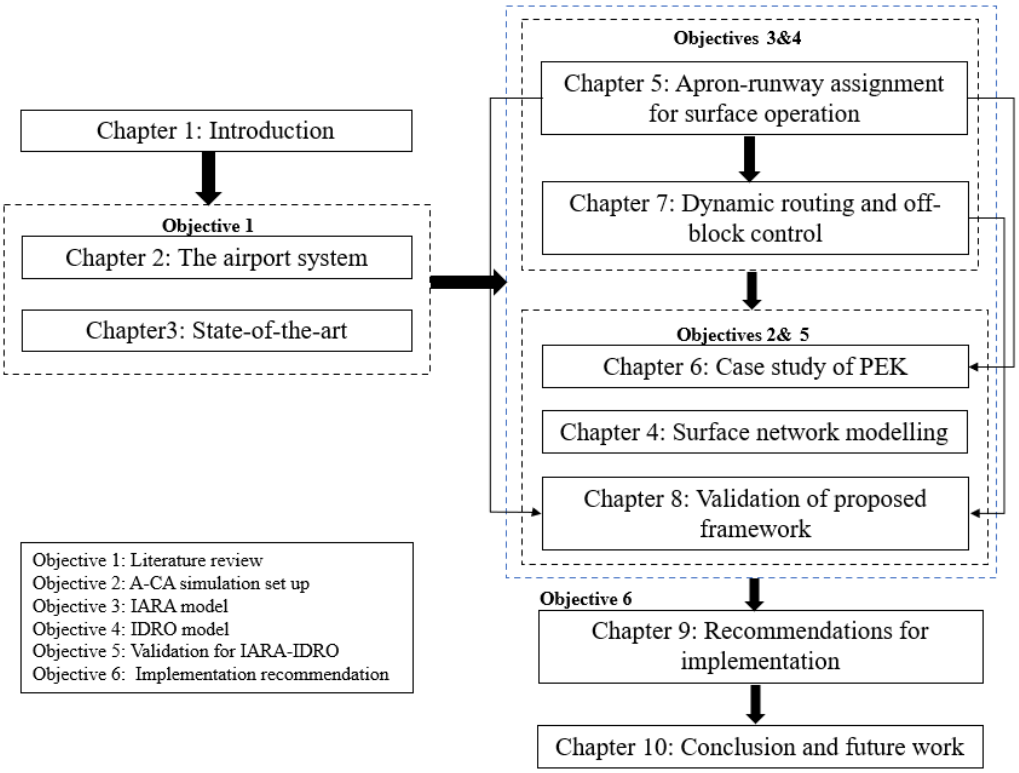

Figure 1.1. Overall structure of the thesis and corresponding objectives

CHAPTER 2 THE AIRPORT SYSTEM

A prerequisite for understanding and evaluating the efficiency of airport surface operation is to properly define the airport environment. This chapter introduces the airport system in terms of its definition, structure, operation, relevant stakeholders, as well as the relevant KPAs and KPIs.

2.1. AIRPORT DEFINITION

By their usage, airports are categorised as civilian and military[1], where the civilian airport is open to the public, and further categorised into air carriers (mainly handling passenger and cargo services) and general aviation. The latter is normally a smaller airport serving privately owned and operated aircraft. This thesis addresses the surface operation of air carrier airports (hereafter referred to as 'airports').

Doc4444 (ICAO, 2016b, p. 1-4) defines the ATM as "*the dynamic, integrated management of air traffic and airspace including* ***air traffic services****,* ***airspace management*** *and* ***air traffic flow management*** *–* ***safely****,* ***economically*** *and* ***efficiently*** *– through the provision of facilities and seamless services in collaboration with all parties and involving airborne and ground-based functions*".

To meet the high-level goals of the Single European Sky (SES), the SESAR Master Plan (SJU, 2015b) outlined the vision to achieve 'high-performing aviation for Europe' in terms of capacity, operational efficiency, environmental impacts, and cost-efficiency, in addition to safety and security, and extended the future plan to 2035 with higher levels of automation, digitalization, and virtualization. This Master Plan redefined SESAR Key Features according to four areas of ATM (optimised ATM network services, advanced air traffic services, **high-**

[1] Some airports both serve military and civil purposes.

performing airport operations and enabling aviation infrastructure) and detailed related essential operational changes of each area in different phases (Pilot Common Project (PCP[2]), new and key R&D activities) to realise the SESAR Concept. Notably, **airport is highlighted in the future European ATM system, which, as a node, will be fully integrated into the network.**

In addition, to achieve performance ambitions that are aligned with the SES High-Level Goals, SESAR outlines potential solutions that are categorised according to the SES KPAs. Within the scope of the airport surface operation, which includes 1) **Operational efficiency** in terms of fuel efficiency expected from enhanced taxi-out management, and time efficiency involving reducing flight delays in arrival, local airport departure and their associated reactionary delay phases; 2) **Increased predictability** expected from additional improvements in taxi-in operation; 3) **Environmental impact** aligned with fuel efficiency for airport surface operation; and 4) **Capacity** through enhancing runway throughput to accommodate additional flights at high-traffic airports.

Furthermore, enhanced airport operations are emphasised in terms of runway throughput, integrated surface management, airport safety nets and total airport management (SJU, 2012a).

To understand the operational background of airports, the rest of this chapter provides a brief introduction to airport components (from the perspective of passengers at terminals), airport operation process (from the perspective of aircraft operation on the surface), as well as relevant stakeholders. This introduction would help to identify key components on the airport surface that shall be integrated into the ATM network, and consequently work out potential solutions for airport surface operation in enabling maximum performance gains. Note that, although advanced Communication[3], Navigation, and Surveillance (CNS) technologies and other

[2] The PCP specifies what should be implemented, where and by whom, as well as when they should be implemented (ICAO, 2015a).
[3] CNS (2014) defined communication as "*between two or more aircraft, the exchange of data or verbal information between aircraft and air traffic control and the ground-based communication infrastructure of the ATM network*".

advanced infrastructures are positive to the airport operation efficiency, they are out of the scope of this research. An introduction to these technologies and procedures can be located in Section 3.1. Instead, this research is concerned with improving aircraft operational efficiency constrained by current resources on the airport surface.

2.2. AIRPORT COMPONENTS

An airport can be divided into landside and airside areas (De Neufville et al, 2013; Horonjeff et al., 1962; Wilke et al, 2014; Studic, 2016), the boundary[4] between the two is the interface (i.e. entry/exit gate) between the passenger's terminal building and the apron. Access to the airside from the landside is strictly controlled. Figure 2.1 illustrates the physical structure and functions of an airport. The arrows represent operation flow for arrival and departure aircraft and passengers. This thesis focuses on aircraft operation on the ***airport surface***[5] (highlighted by the red circle in Figure 2.1), which is on the airside of the airport, consisting of the runway, taxiway, and apron systems. In this thesis, the airport surface is to be expressed as a transport network represented as a graph with nodes and (directed or undirected) links. The origins and destinations of the network are aprons and runways, and each aircraft passing through the network is assigned an origin-destination (O-D) pair and route to follow.

2.2.1. Airport Landside

The landside typically consists of passengers' terminal and ground access system (e.g. railway system, road system). The terminal's area is associated with passenger's activities including pre-departure and after-arrival services. This can be divided into publicly accessible side and restricted areas. The public area generally covers ticketing, inquiry and information encounters,

[4] Notably, no common understanding about the boundary between the airside and the landside. Besides the definition adopted in question, security control is considered as the boundary.
[5] Airport surface, as known as ground movement area. In US, apron is excluded in the movement area, while in Canada, China, EU, who adopted the definition by ICAO that the ground movement includes the apron. In this research, the definition is adopted from ICAO that the movement area consists of runway, taxiway, and apron.

check-in, and arrivals areas, while restricted areas include security checks, immigration checks (only for international flights) and waiting areas for departure passengers who must hold valid tickets and ID cards to access and include luggage area for arrival passengers. The locations of the luggage areas may be different, e.g. within the restricted area in EU and Asia airports, and in the public area in U.S. airports (Wilke, 2012; Wilke et al., 2013&2014).

Figure 2.2 shows an example of the interior structure of an airport terminal. The passenger's activities in terms of pre-flight and post-flight are introduced in Section 2.3.1.

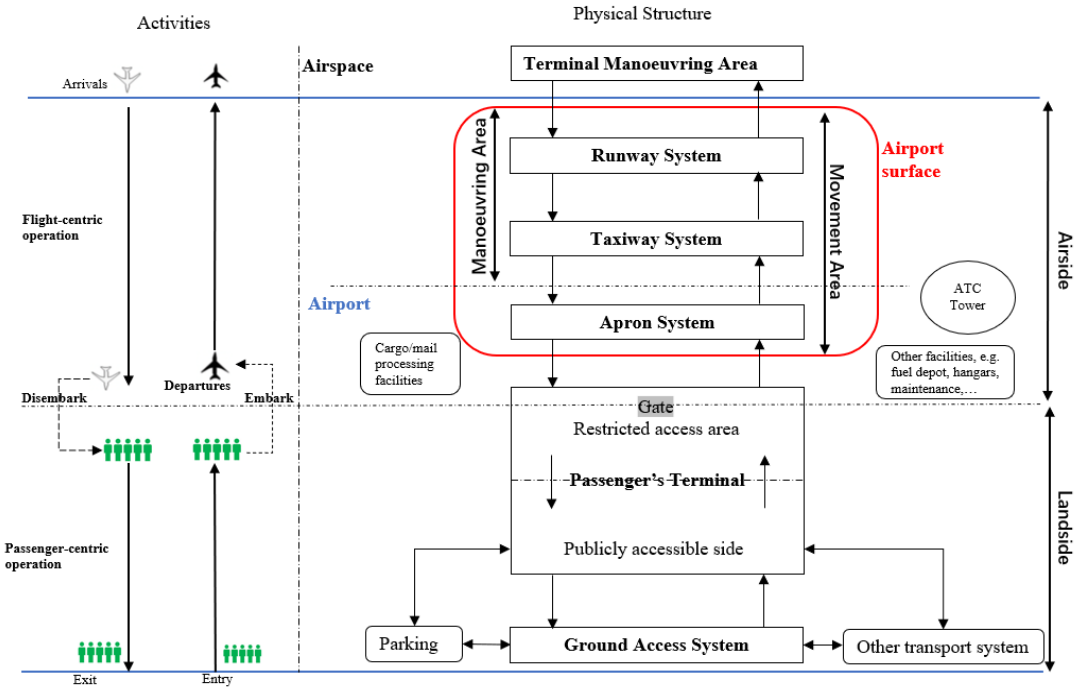

Figure 2.1. Physical structure and functions of an airport

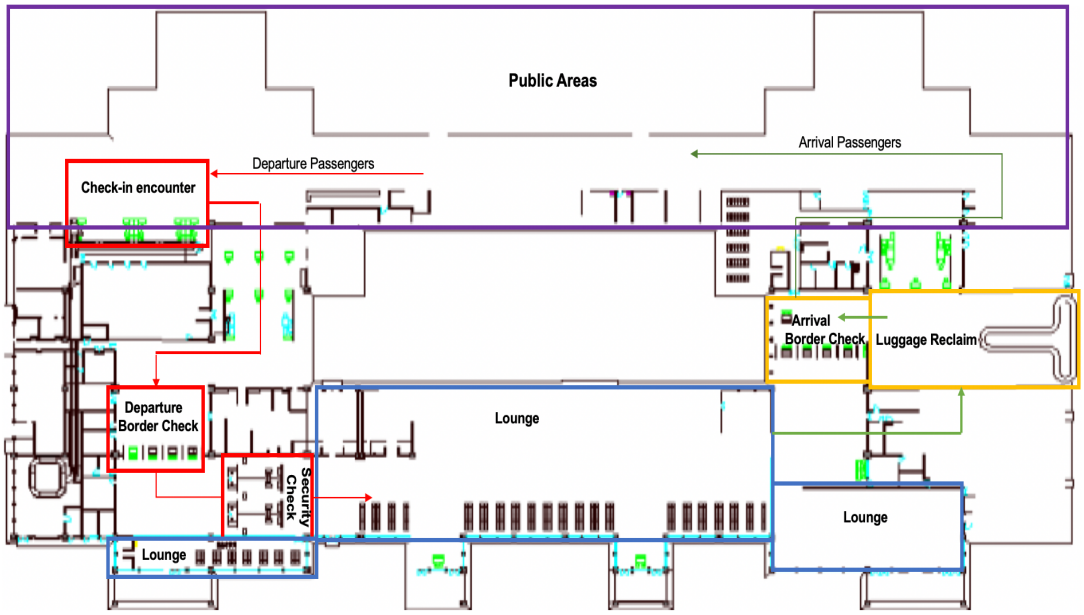

Figure 2.2. Example of a physical structure of an International Airport Terminal

2.2.2. Airport Airside

The airside, also known as airfield, is mainly functioned for aircraft's activities, including the **apron system** used for parking and ground handling services, the **taxiway system** for taxiing, the **runway system** for both landing and take-off, and other associated infrastructures (e.g., ATC tower[6], lighting system, markings and signs). In addition, cargo and mail processing, fire station, hangars, and other facilities (e.g., de-icing area) may be located in the airside area as well (see Figure 2.1).

Furthermore, within the airside, "*the part of an aerodrome to be used for the take-off, landing, and taxiing of aircraft, consisting of the manoeuvring area (**taxiway system** and **runway system**) and the **apron system***", is defined as the movement area by International Civil Aviation

[6] An ATC tower may be located in the landside (e.g. LAX), or in the airside (e.g. PEK), or other places (e.g. remote tower) that needs to meet the requirement of supervising the operation of the aircraft moving on the airport surface.

Organisation (ICAO, 2016a, p. 1-12), also defined as the **airport surface** in this research. Figure 2.1 shows the structure of a conceptual airport, and the area of the airport surface, consisting of runways, taxiways, and aprons, is highlighted by the red circle. Detail operation activities on each system are introduced in Section 2.3.2.

2.2.2.1. Apron system

An apron is defined by ICAO as "*a defined area intended to accommodate aircraft for purposes of loading and unloading passengers, mail or cargo, fuelling and parking or maintenance"* (ICAO, 2016a, p. 1-5), consisting of stands[7] for parking aircraft, as well as infrastructural elements (e.g. apron taxiway, apron stand taxi lane). Aprons are normally controlled by either ATCOs, or apron management service, to provide coordination among the users (ICAO, 2018). According to the types of aircraft stands, aprons can be categorised into:

- Passenger terminal aprons, which are adjacent to or accessible from passenger terminal facilities;
- Cargo terminal aprons, which are adjacent to a cargo building;
- Remote parking aprons, a separate parking area where a transporter is required to transport passengers, baggage, and cargos to and from the passenger's terminal;
- Service aprons, which are open areas adjacent to an aircraft hangar that can be used for aircraft maintenance;
- Hangar aprons, areas where aircraft enter and exit storage hangars; and General aviation aprons, which are used for parking and supporting different general aviation activities, either for business or personal travel purposes.

Furthermore, passenger terminal aprons can be further divided into remote and contact stands. The contact stands, also known as bridge stands, are close to the passenger building, while the remote stands are usually far from the building, so that passengers normally take a shuttle bus

[7] Stands and gates, which are often interchangeably used, are places on the airport surface that intend to be used for aircraft parking (ICAO, 2005b).

or car to board. Normally, it is more convenient for the passengers to board via bridge stands, and therefore, the number of the gate assignments are often considered as a criterion to evaluate the airport/airline service quality.

This research focusses on the utilisation of **passenger terminal apron** and **remote parking apron** that are directly related to passenger demands. Other types of aprons are outside the scope of this research.

Although the basic function of passenger apron is the same, the structure of aprons can be considerably different. It is noted that the passenger terminal directly connects to the stands of the apron, thus various apron structures are associated with distinct movements in terms of for example, taxi time, taxi distance, taxi route, and conflicts. There are five basic configurations of passenger terminal buildings and aprons, as follows.

A. Simple box

This is normally suitable to airports with low traffic demands (i.e. annual passenger volume lower than 1 million). Such a construction allows aircraft to self-taxi in and out the stand, given adequate clearance between the apron and the terminal (see Figure 2.3a).

B. Linear buildings

The linear structure can be thought of as a step up from the simple box, which can accommodate more flight demands (i.e. annual passenger volume around 1-5 millions). In this structure, the aircraft can taxi in by itself and pushed back by towing tractors. Little disruption in neighbouring gates is expected during pushback (see Figure 2.3b).

C. Finger Piers

This is named after the structure from a bird view that looks like fingers attached to a hand's palm (see Figure 2.3c). Normally, gates are located on both sides of the structure, extending

away from the Centre Core in this design. Passengers walking to the gates somewhere close to the Centre Core is more convenient than gates located at the end of the "fingers".

D. Satellites

The terminal building resembles a satellite, unlike gates located along the fingers, all gates are concentrated at the end (see Figure 2.3d). The aircraft can be pared around the satellite in radial, parallel, or other configurations depending on the specific shape of the satellite. Push-back processes are dependent on parking configuration of the apron. For example, if the aircraft is parked radially, the operation is simple but needs more apron space. However, if the aircraft is parked in a wedge-shaped, it would result in not only long taxi time within the apron due to inevitable sharp turnings, but also cause congestion in and around the satellite area.

E. Transporters

This kind of aprons usually refer to remote aprons or an open or transporter ones, which may be located away from other structures or close to the runway. It requires transporting passengers, baggage and cargo by vehicles (i.e. shuttle bus, mobile lounges) and carts to and from the passenger's terminal (see Figure 2.3e).

In addition to the parking stands within the apron, other facilities include apron taxiways, stand taxi lane, and service roads to access the aircraft stand and provide necessary services, apron signage and apron markings to segregate aircraft from other traffic and aircraft, as well as lightings for low visibility and night conditions (ICAO, 2005a).

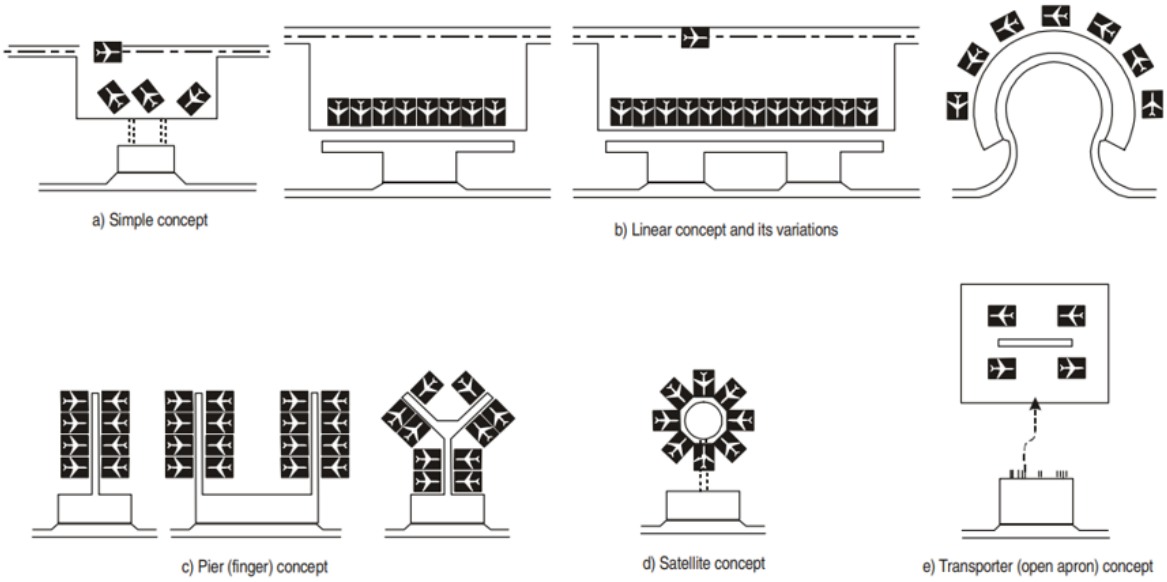

Figure 2.3. Passenger terminal apron structure concepts (adopted from ICAO (2005b))

2.2.2.2. Runway system

ICAO (2016c, p. 1-15) defined the runway as "*a rectangular area on a land aerodrome prepared for the landing and take-off of aircraft*. Runway connects the airport surface to the airspace, whose throughput is highly related to the airport capacity. This section introduces basic information of the runways in terms of naming convention and spatial configurations.

1) Runway Name

Each runway has a name, using a two-digit number between 01 and 36, which is defined as the angle between the magnetic North[8] and the runway's heading in decadegrees (FAA, 2012b). For example, RWY 01 means that the runway's heading is around 10° east of the magnetic north, RWY 09 points to the east (90°), and RWY 36 points to the north (it is notable that 360°

[8] It is notable that the magnetic north differs from the true north by the local magnetic declination.

is not 0°). A runway may generally be utilised in two directions, each of which is labelled individually, with the two numerals differing by 18 (=180°). For example, if RWY 01 is named in one direction, RWY 19 is in the other direction. For parallel runways, as both go in the same direction, a letter L (for left) and R (for right) are used behind the runway number. For example, as the two westerly parallel runways have a heading of 271 degrees in Heathrow International Airport (IATA: LHR), they are numbered 27L/09R and 27R/09L, respectively. For three parallel runways, an extra letter C (for centre) is used, e.g. 18L, 18C and 18R corresponding to 36R, 36C and 36L, while L or R is determined from runway's heading direction (its facing direction). For more than three parallel runways, L, R and C are not enough to number all runways, thus, a number with 10 degrees increment is designated for the runway name. For example, among the seven parallel runways are at Dallas- Fort Worth International Airport (IATA: DFW), five are parallel, and named 17L/35R, 17C/35C, 17R/35L, 18L/36R and 18R/36L.

2) Runway Configurations

Runways connect the airport surface and the airspace. Not only is its configuration related to the airport capacity, it also has an impact on the complexity of the airspace terminal. There are four basic types of runway configurations, Single Runway, Parallel Runways, Open V Runways, and Intersecting Runways (Crossover Runways). For larger airports, the configuration is the combination of two or more basic configurations.

- **Single Runway** means only one runway in the airside of the airport, such as Kona International Airport (IATA: KOA, USA), Qingdao Liuting International Airport (IATA: TAO, China), and Stansted International Airport (STN, UK). Every single runway has two opposite directions. Taking STN as an example (see Figure 2.5), the runway is numbered 04/22, which means that the intersection angle of the runway heading and the magnetic azimuth is 40° and 220° from two different directions, respectively.

- **Parallel Runways** are defined as runways whose extended centrelines diverge or converge by 15 degrees or less, but without crossover of each other. The capacity of the parallel runways depends on the number of runways that can be used simultaneously and the spacing between each other. The spacing between runways is classified as close (700 feet-2500 feet), intermedium (2500 feet-4300 feet) and far apart (over 4300 feet). Close runways are dependent, which means that only one runway can be operated at a time. Intermedium runways are less dependent, as the runways can in principle be operated at the same time, yet subject to conditions such as one runway is for arrival and the other for departure. If there are more than two runways in parallel, the runways can be alternately operated for arrival and departure. Figure 2.5 shows examples of two parallel runways at LHR), three parallel runways at PEK, and four parallel runways at ATL, respectively. The far-apart runways are independent, which can in principle be operated simultaneously. Every runway can be operated for arrival or departure, or both for arrival and departure, and has no influence on each other.

- **Open V Runways** usually have one end close to each other and form a V-shape (usually the angle is larger than 15 degree); however, the runways do not intersect with each other. Such a configuration is normally constrained by relatively strong prevailing winds from more than two directions, while the single or parallel runways (with only one or two directions) do not meet all kinds of take-off requirement, as the aircraft should take off against the wind direction. In this case, when the winds become strong in one direction, only one runway will be used. When take-offs and landings are made away from the two-closer ends (see Figure 2.4(b)), the throughput of runways theoretically increases. The number of operations at runways significantly drops when the winds are against the two- closer ends.
- **Intersecting Runways** mean two or more runways whose centrelines cross each other. This type of configuration is developed given relatively strong prevailing winds from more than one direction. Such a configuration increases the difficulty of the operational programme as the crossed runways are always dependent on each other when being

operated simultaneously. On the other hand, when the winds are strong from one direction, operation is limited to only one of the runways, which leads to drastically decreased operation throughput, especially during peak hours.

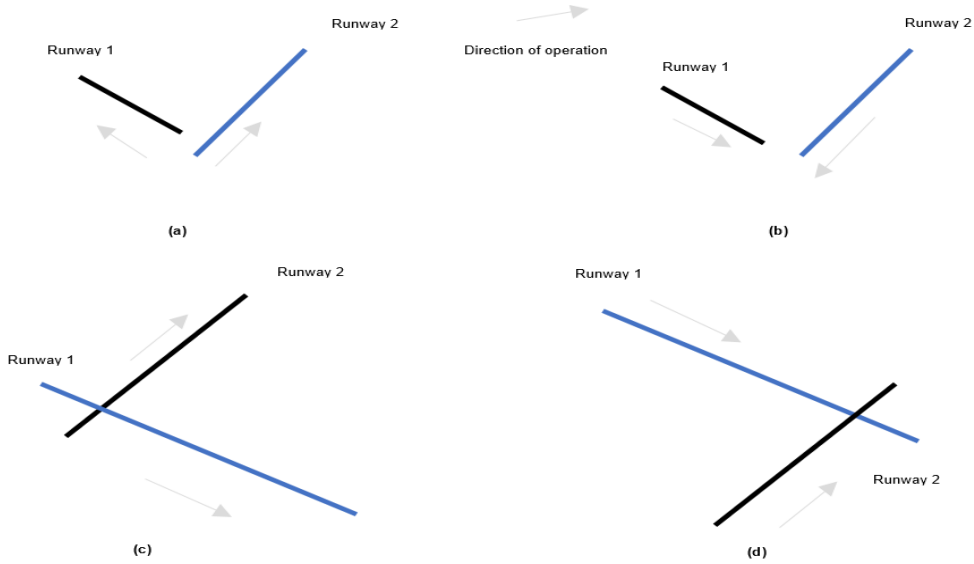

Figure 2.4. Open V with dependent operations away from the intersection; (b) Open V with dependent operations towards the intersection; (c) Intersecting runways with dependent operations away from the cross point; (d) Intersecting runways with dependent operations

Figure 2.5 shows the classification of runway configurations around the globe. An airport with a single runway, whose throughput is relatively less than that of large airports with more than one runway, mainly operates regional flights. For example, Stansted International Airport (IATA: STN), Qingdao Liuting International Airport in China (IATA: TAO), and Kona International Airport (IATA: KOA) are typical airports with a single runway.

Parallel runways are the most widely seen, such as London Heathrow International Airport (IATA: LHR) with two runways operating independently (the spacing between runways are greater than 4300 feet), Beijing Capital International Airport (IATA: PEK) with three runways (all the runways can be operated independently). Hartsfield-Jackson Atlanta International

Airport has five runways in parallel, (8L/26R, 8R/26L, 9L/27R, 9R/27L,10/28), outnumbering any other airports in the world. In particular, runway pairs (8L/26R, 8R/26L) and (9L/27R, 9R/27L) are intermedium runways, while runway 10/28 is distant to others. The third row of the figure shows examples of "Open V runways", which do not exist in the UK but can be found in the number of countries in the EU, such as FRA in Germany, BVA and CFE in France. In China, most of the multi-runway configurations are parallel, except the newest and largest airport, Beijing Daxing International Airport (PKX), which is currently operating four runways (01L/19R, 17L/35R, 17R/35L, and 11L/29R), with the fifth one under construction. This configuration is more common in the US, such as George Bush Intercontinental Airport (IATA: IAH) (see Figure 2.5), Denver International Airport (IATA: DEN) and Washington Dulles International Airport (IATA: IAD). The intersecting runways configuration is illustrated in Figure 2.5. This type of runway configuration is not seen in China or the UK, but in some EU airports like Paris Orly Airport (IATA: ORY) in France, Amsterdam Airport Schiphol (IATA: AMS) in Holland, and Helsinki Airport (IATA: HEL) in Finland. This configuration is also seen in the US, such as O'Hare International Airport (IATA: ORD), Dallas-Fort Worth International Airport (IATA: DFW), and Detroit Metropolitan Airport (IATA: DTW).

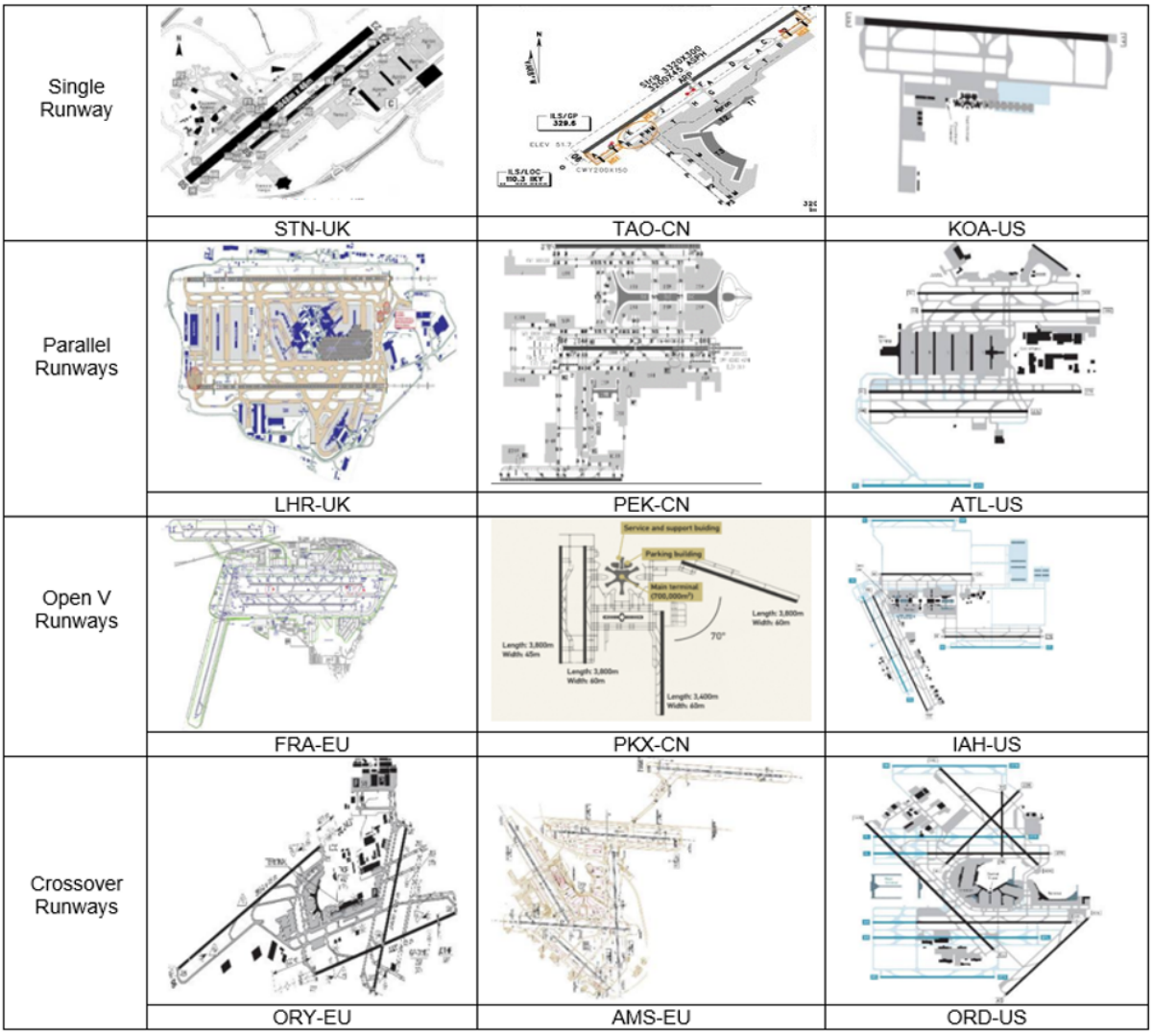

Figure 2.5. Examples of the classification of runway configurations around the globe (Yin, 2016)

2.2.2.3. Taxiway system

ICAO (2016c, p.1-16) defined the taxiway as "a defined path on a land aerodrome established for the taxiing of aircraft and intended to provide a link between one part of the aerodrome and another". Most airports have speed limits depending on the locations somewhere at curves, runway exits, apron taxiway, also some airlines have taxiing rule itself, like maximum taxi speed on the straight taxiway or at turnings that normally lower than the requirement determined by the airport.

1) High-speed exits

A special taxiway namely high-speed exits are usually constructed at airports with high traffic volume, which connect to a runway, aiming at reducing runway occupancy times by allowing landing aircraft to turn off at higher speeds than are possible on other exit taxiways. This is achieved by reducing the angle at which the exit taxiway intercepts the runway to 30 degrees instead of 90 degrees, thereby allowing the aircraft to exit the runway at a higher speed.

2) Apron taxiway and stand taxi lane

Apron taxiways, stand taxi lane, and service roads are used to access the aircraft stand as well as to provide necessary services. Figure 2.6 shows taxiways and lead-in lines on an apron. Two types of taxiways located on aprons, where apron taxiway provides either a through route across the apron or access to the aircraft taxilane, while the aircraft stand taxilane is designated as a taxiway intended exclusively for access to aircraft stands. Moreover, aircraft stand lead-in lines to parking positions are not considered as part of a taxilane and therefore exempt from the requirements for taxiways.

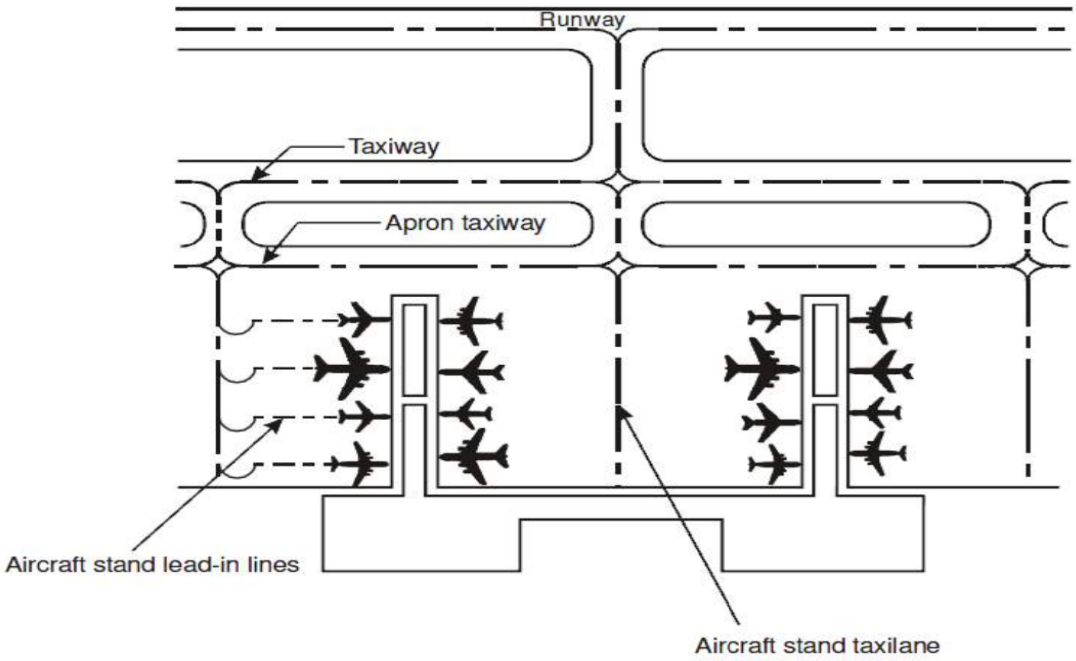

Figure 2.6. Apron taxiway, stand taxi lane and lead-in lines (adopted from ICAO (2005b))

In addition, the signages and markings, as well as lighting systems for low visibility conditions, are also required on the airport surface according to ICAO (2005a). For more details refer to (ACI, 2007; ICAO, 2005a; Jacquillat and Odoni, 2015).

2.3. AIRPORT OPERATION

To further understand the operational background of airports, this section provides a brief introduction to the airport operation, from the perspective of passenger service process in the passenger's terminal, and that of aircraft operational processes on the airport surface.

2.3.1. Passenger-centric Operation in the Passenger's Terminal

Passengers' terminals in general cover a series of functional areas designated for pre-departure and after-arrival services (e.g. ticketing, check-in, security, immigration check, and baggage claim). It is noted that, although terminals in different airports within the EU, the US and Asia vary by number and shape, the general operational processes for passengers are similar. In general, this process can be classified into four categories, international departures, national departures, international arrivals, and national arrivals. Figure 2.7(a)-(b) show the four general processes, respectively. Once passengers reach the gate, they are transferred between the landside and the airside.

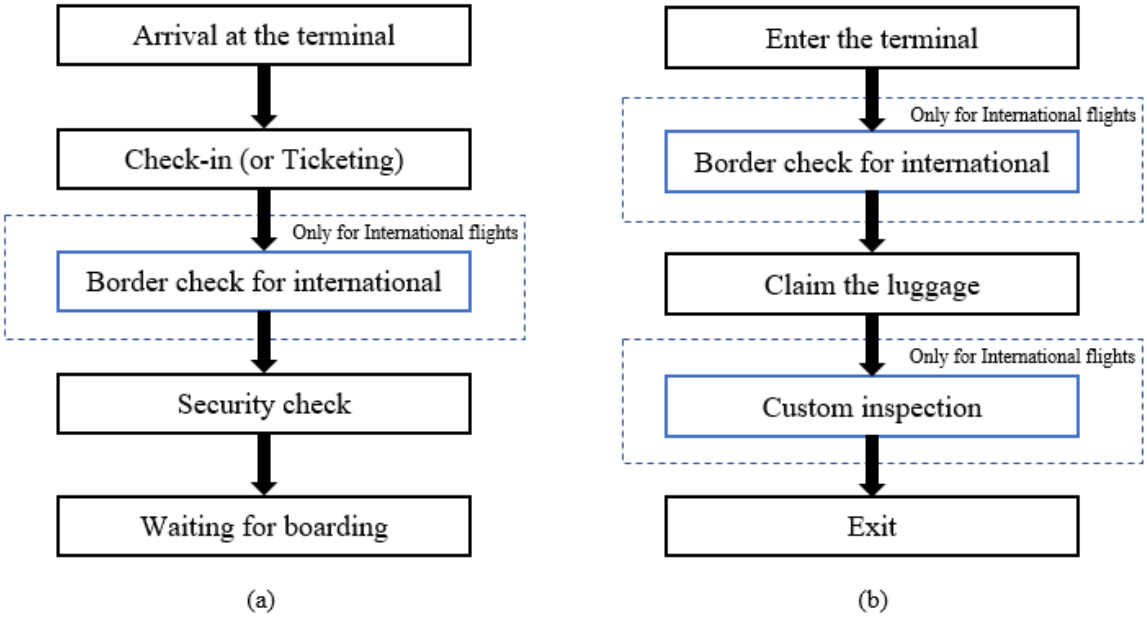

Figure 2.7. (a) Departure process of passengers; (b) Arrival process of passengers. The process circled in the box only for international flights

2.3.2. Aircraft-centric Operation on the Airport Surface

This section introduces the airport operation process on the airside. It is concerned with the general operational process, noting that slight differences in various airports (EUROCONTROL, 2005) may exist. The operational process [9]begins with the approaching phase in the Terminal Manoeuvring Area (TMA)[10], followed by specific activities on the airport surface from the perspective of aircraft operation.

Approaching: Terminal Controllers (TC) control and sequence aircraft prior to handing over control to the Tower Arrival Controller, the TC is responsible for managing air traffic flow and issuing landing clearance or holding delays. In this phase, once the landing clearance is approved, **the runway for arrivals** is being assigned to the aircraft.

Landing: After the aircraft is handed to the Tower Controller (TWR), the aircraft will be instructed and monitored by the TWR for final approach. The Controller will give the aircraft landing clearance at the appropriate time with some relevant information (confirmation of runway in use for arrival, surface conditions and local weather condition).

Stand Allocation: When the aircraft is on final approach or has landed, the stand will be allocated to the aircraft by Airport Stand Planner. After landing, the Tower Ground Management Controller (TWR GMC) will instruct the aircraft to the allocated stand, taxiing along a specific route.

Taxi in: Once the aircraft stand allocation is issued, the Ground Handling (GH) will receive the aircraft location immediately and get in position to 'set up' the stand for receiving the aircraft and perform the ground handling services (e.g. fuelling, cleaning, loading). The in-block time is captured manually by the GH or automatically from Airborne Collision

[9] Note that, approaching phase is excluded in the airport surface operation. Staring with the approach phase is to ensure the continuity and integrity of the operation process within the airport airside.
[10] A designated controlled airspace surrounding a major airport is known as TMA in EU, or as a Terminal Control Area (TCA) in the US and Canada (ICAO, 2007; FAA, 2019).

Avoidance System (ACARS)-equipped aircraft when the pilot applies the aircraft parking brake.

Parking (Turn-around): The airline dispatcher will oversee the whole turn-around activities (such as embarkation or disembarkation, loading or unloading) and will advise the pilot when turn-around activities are completed and the aircraft is ready for push back.

Taxi out: When the aircraft is ready to be pushed back, the pilot contacts the TWR and requests for approval of push-back and start-up. Once the pushback clearance is approved, the TWR GMC issues departure information (i.e. start-up point, the **taxiing route**, holding point and **assigned runway for the departure aircraft**), and the aircraft crew instructs the ground handling crew to push back the aircraft to the designated start-up point via headset.

Take-off: When the aircraft arrives at the designated holding point of the runway, the GMC hands over the aircraft control to the TWR Controller (Departure). The TWR then issues take-off clearance at the appropriate time and instructs the pilot to the Approach/Terminal Controller on a pre-set frequency for further instructions.

Figure 2.8 shows a general aircraft operational process on the airport surface. It is shown that the entire operation process of an aircraft on the airport surface[11] includes **taxi-in process** in terms of landing and exiting the runway (the origin of arrivals), taxiing in (routing assignment for departures), parking (the destination/origin of arrivals/departures), and **taxi-out process** covering pushback from the stand, taxiing out (off-block time and routing assignment), and take off (runway assignment).

Overall, in addition to the physical connections among the three components (runway, taxiway, and apron), all the activities taking place are also interconnected and interdependent. Any

[11] It is noted that, for a pair of connecting flights, both processes are included, while for a single arrival/departure flight, only taxi-in/taxi-out process is required.

change made in one of the operational components is likely to trigger a ripple effect in terms of aircraft movement on the others.

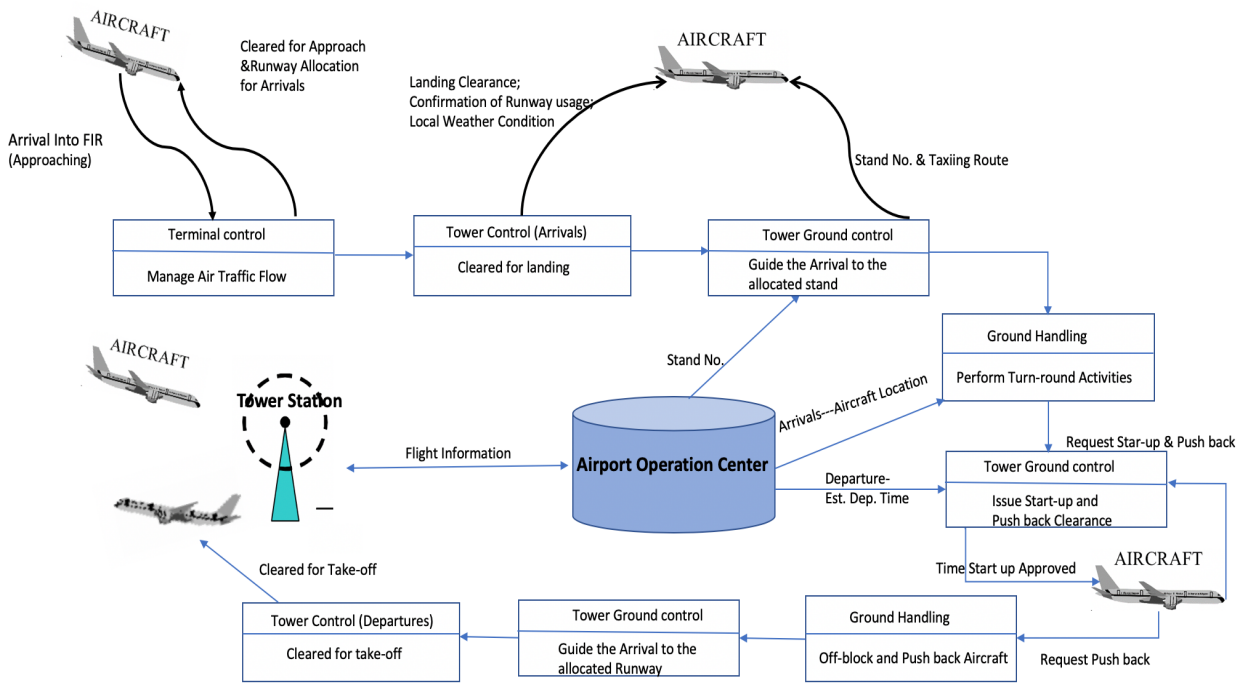

Figure 2.8. Diagrammatic overview of airport operation process (EUROCONTROL, 2005)

2.4 STAKEHOLDERS FOR AIRPORT SURFACE OPERATION

2.4.1. Airport Authority

The **airport authority（airport operator）** is a governmental or non-governmental entity, which owns, operates, and manages an airport or a group of airports, and is responsible for the management and oversight of airport operation. Typical activities of an airport authority involve:

- The construction and development of airport infrastructure and facilities for the airside (including runway systems, taxiway systems, apron systems, surface marking and lighting) and the landside (including required facilities within passenger terminals and linked ground transport system);
- The security of controlled areas (passengers and staff must be checked by security before being permitted to enter the controlled area);
- The establishment and enforcement of airside procedures and processes, airside driving, apron cleanliness; and
- The collection, investigation, analysis of information and dissemination of lessons learned from any incidents that take place on the airside (i.e. safety reporting, inspections).

There are mainly four key personnel or departments, which are responsible for airside operation within the airport (SJU, 2014e).

- **The Airport Duty Officer** is responsible for ensuring that the airport is operated in accordance with international and national regulations and is in a safe condition.
- **The Airport Operation Centre** (APOC) is the central organizational unit, which is responsible for the airport's airside operation. In order to establish a harmonised environment for collaborative airport planning among the different actors (airport operation, airlines, ANSPs), SESAR APOC concept was proposed, which is considered one means for addressing the efficiency of overall airport operations.
- **The Apron Manager** is responsible for ensuring activities and movements of mobiles (e.g. aircraft, vehicle) safe and efficient, within the controlled area in accordance with local procedures, as well as for the guidance of aircraft taxiing-in the stand or pushback from the stand. Moreover, the apron manager works closely with other stakeholders including ATCOs, Airport Operation Control Centre (AOCC) and APOC on the decision-making of planned flights.
- **The Stand Planner** assigns a stand to each arriving aircraft, taking into account a set of constraints, including aircraft type, aircraft load (passenger or cargo), gate attribute

(some gates may only be used for designated airlines), and aircraft attribute (e.g., international, domestic, Schengen, general aviation). The stand plan is dynamically modified to comply with real-time constraints (such as stand usage conflict, flight delays, technical problems with a stand) in the medium or short term, and the plan is iterated, when necessary, up to and including the execution phase (SJU, 2012b).

2.4.2. Ground Handling

Ground Service Provider (GSP) supplies "the ground services necessary for the arrival and departure of an aircraft in an airport, other than air traffic services" (ICAO, 2010, p. 1-6; IATA, 2013, p.45; IATA, 2021, p.57). The specific composition of the GSP team varies widely across the airports of the world, which may be undertaken by the airport authority, independent ground handling companies, or airlines (ARC, 2009). The objective of the GSP is to execute the aircraft turn-around guaranteed service, based on the signed ground handling service level agreements. Moreover, in order to guarantee that ground operations are carried out in a safe, efficient, and consistent manner, IATA Ground Operations Manual (IGOM) has defined ground handling standards. The scope of ground handling and the standard procedures for ground handling is explicitly specified in IATA (2015). The specific activities of GSP are summarised in following subsections.

2.4.2.1. Passenger handling

Passenger handling in terms of pre-departure and -arrival activities include:

- Ticket sale;
- Pre-flight preparation and facilitation of special passenger's groups;
- Check-in and baggage drop-off services;
- Verification of travel documents;
- Security screening;
- Embarkation and disembarkation; and
- Flight documents.

Post-flight departure activities include:

- Required message information reporting and Electronic Ticket List (ETL); and
- Preparation of jet-bridge for contact stands, or a shuttle bus or walking guidance for remote stands.

2.4.2.2. Baggage handling

The types of baggage to be managed includes:

- Cabin baggage;
- Checked baggage (which should be packaged and labelled with passenger ID); and
- Special baggage.

Baggage handling also involves baggage security and dealing with mishandled baggage.

2.4.2.3. Aircraft handling

Aircraft handling includes:

- Apron safety (including all activities, equipment and facilities within the apron);
- Aircraft servicing (i.e. potable water, cleaning, de/anti-icing, catering);
- Aircraft fueling/defueling; and
- Ground operator servicing (i.e. cones/wheel chock placement and removal, hand signals, pushback, engine start, tractor usage and wing walking.

It also incorporates ground support equipment (ground power units, the cooling and heating units) and load control (Studic 2013& 2014 &2016).

2.4.2.4. Airside supervision and safety

All station activities should be conducted under the direct oversight of supervision staff, in order to guarantee ground operational safety. The scope of the supervision includes:

- Aircraft loading or unloading;
- Aircraft servicing (i.e. potable water, cleaning, de/anti-icing, catering);
- Aircraft fuelling and defueling;
- Aircraft activities (e.g. taxiing-in, taxiing-out, towing procedures);
- Passenger embarkation and disembarkation; and
- Handling of excess cabin baggage.

2.4.3. Airlines

The airline is a commercial company, which is recognised by an operating certificate or license issued by the National Aviation Authorities (NAA), to provide air transport services for carrying passengers and freight. During the turn-around process, the airline operation mainly includes aircraft operation (i.e. pre-departure procedures, departure, taxiing, and arrival as well as post-departure and -arrival activities), passenger embarkation and disembarkation, aircraft security and maintenance, loading and unloading freight, and some other ground handling service (Studic et al., 2015).

An airline alliance provides marketing branding allowing travellers to make inter-airline codeshare connections within countries. The main airline alliances include Star Alliance, One-world and SkyTeam. Apart from the three main airline alliances, there are some smaller alliance groups, for example, Vanilla Alliance, U-FLY Alliance, and Value Alliance. Because of the sharing of services within an airline alliance, the distribution of the airport facilities between the airlines within the airport terminal normally takes alliance membership into account, which is a restriction or regulation that affects the assignment of gates or stands. For example, in the LHR, Terminal 2 is assigned to Star Alliance, Terminal 4 is assigned to SkyTeam, Terminal 5 is assigned to British Airways, and the remaining airlines are located in Terminal 3.

In addition to airline crew (flight crew and cabin crew) within the aircraft, there is another critical component, the flight control centre, that plays an extremely part in aircraft operation. It is usually known as the **Operational Control Centre (OCC).** OCC support components include (O'Brien, 2008)

- Operational coordination (i.e. airport management liaison, and traffic control collaborating with the airport and ATC);
- Operational liaison (i.e. authorising the flight with the chief pilot, and contacting base representatives during the flight); and
- Operational support (i.e. security and safety, as well as data management and analysis in terms of delays and costs).

2.4.4. Air Traffic Control (ATC)

Air Traffic Control (ATC) is a service provided by ground-based ATCOs who direct aircraft on the ground and through controlled airspace, in addition to provide advisory services to aircraft in non-controlled airspace. The main responsibilities of ATC are to prevent collisions, organise and expedite air traffic flow, as well as provide information and other assistance to pilots throughout the world. From the perspective of the job responsibility, ATC is mainly divided into three areas of responsibility: tower control, approach or terminal control and en-route or area control, whereas tower control and terminal control are the direct stakeholders in airport operation. The details of each control are introduced as follows:

Tower control is generally composed of ground control and local control:

- **Local control** is responsible for the active runway surfaces, including issuing clearance for take-off or landing for each flight at the appropriate time, by considering the safe separation distance between aircraft, weather conditions, and so forth. If it detects any unsafe conditions, a landing aircraft might be instructed to “go-around” procedure, whilst an aircraft ready to take off would be required to wait in a given holding area until the unsafe condition no longer exists.

- **Ground Control** generally covers taxiways, as well as some transitional areas or intersections, such as inactive runways, the interfaces of aprons and taxiways, holding areas, departure gates. Clearances are required for any mobiles (e.g., aircraft, vehicle) and person when walking or working in these areas. Ground control, which is highly related to pre-departure sequencing, is of importance for airport operation in terms of safety and efficiency.

Approach/Terminal Control is to provide all ATC services within terminal airspace, which is usually in a 56 to 93km radius around the airport. The controlled airspace boundaries vary widely from airport to airport; they are determined mainly according to traffic flow, neighbouring airports, and terrain. Terminal control may be shared by some airports, if they are located very close. For example, the London Terminal Control Centre supports ATC services for five airports in and around London: Heathrow Airport, Gatwick Airport, Stansted Airport, Luton Airport, and London City Airport.

Terminal Control is responsible for traffic flow in terms of departing, arriving, and overflights. It should ensure aircraft flying at a proper altitude or a suitable rate when they are handed off to the next control facility (e.g. a tower control, an en-route control, a broader approach control).

2.4.5. Network Manager

Commission Regulation (EU) N° 677/2011 introduced the Network Manager (NM) as "*the operational arm of the Single European System (SES) and manages air traffic management network functions (airspace design, flow management) as well as scarce resources (transponder code allocations, radio frequencies)*". The overall goal of the NM is to improve ATM performance across the European network, in terms of safety, capacity, environmental impacts, operational efficiency, and cost-effectiveness, by addressing performance issues strategically, operationally, and technically. The Network Manager conducts four main functions mandated by the European Commission (Commission Regulation, 2011):

- The creation and development of route network design;
- The provision of a central authority for frequency allocation;
- Coordinated improvements to SSR code allocation; and
- Conduction of the ATFM function.

The NM benefits Europe's ATM system, as well as the airports which are subsequently integrated into the ATM network in the future by:

- Helping ANSPs, airspace users, and airports to enhance network performance throughout Europe;
- Jointly drawing up a strategy, plans and priorities;
- Helping to make routes more efficient;
- Balancing demand and capacity;
- Managing scarce resources;
- Consolidating information into centralized ATM databases;
- Helping to underpin collaborative decision-making;
- Forecasting, monitoring, and analysing network performance;
- Dealing with network challenges centrally - weather, major events, hotspots, crises.

According to the specific introduction above, the objective of all stakeholders for airport operation is shown in Figure 2.9, which is also the common objective amongst stakeholders in A-CDM (EUROCONTROL, 2015).

2.4.6. Air Navigation Service Providers

Air Navigation Service Providers (ANSPs) provide air navigation services including ATM, a Communication, Navigation, and Surveillance system (CNS), a meteorological (MET) service for air navigation, search and rescue (SAR), and Aeronautical Information Services (AIS), to air traffic during all phases of operations (airport, TMA, and en-route) (ICAO, 2013, p. xi)

Figure 2.9 is an example from the Australian A-CDM system, showing how various stakeholders working together to share data of each step on the A-CDM platform. To keep the continuity, it starts from the taxi-out process of the previous flight segment, as once the aircraft departs, the Actual Take-off Time (ATOT) is recorded into the A-CDM by ATC, the ELDT and other data are calculated and updated according to a real-time situation of the target aircraft. The collaboration on the airport surface operation is highlighted by the red circle, where the ATC is responsible for the entire process, working with the airport concerning the taxiing process and with the ground handler for the turn-around process, respectively. The ANSP provides services for all the phases of aircraft operation, and the network manager manages the ATM network function and scarce resources. The details of each stakeholder refer to Sections 2.4.1-2.4.5.

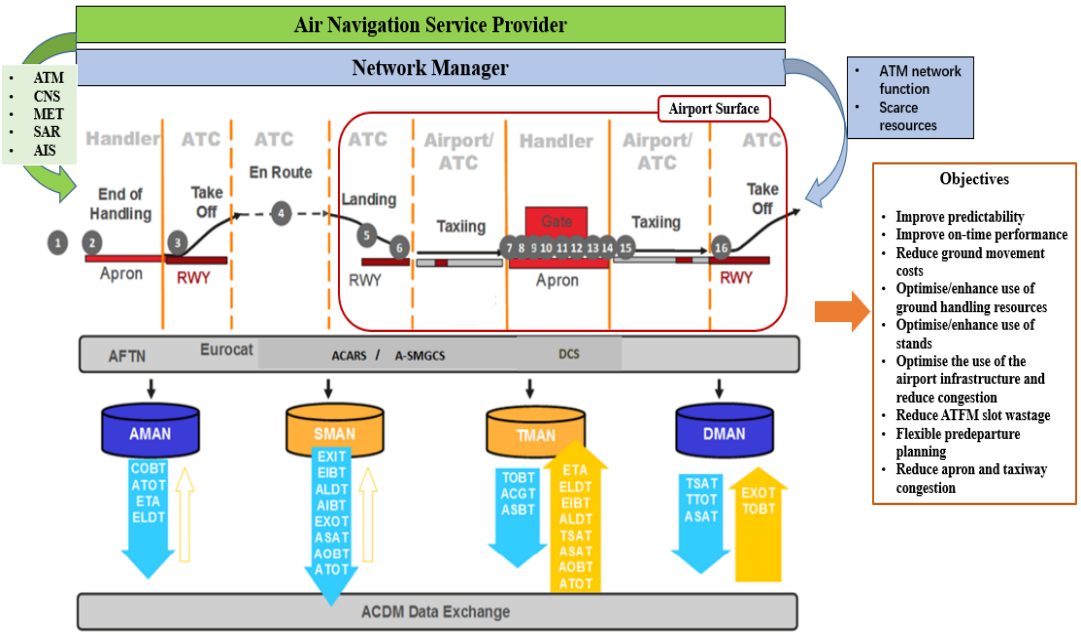

Figure 2.9. Stakeholders on the airport surface operation (adopted from EUROCONTROL, 2015)

2.5 KEY PERFORMANCE AREAS AND INDICATORS

Airport performance is measured by means of Key Performance Areas (KPAs). Due to the increasing demands of civil aviation that often exceed the accommodated capacity of the Air Navigation System (ANS), a Global Air Traffic Management Operational Concept (Global ATM ConOps) with a perspective of ***an integrated, harmonised and globally interoperable ATM system*** up to 2025 and beyond, was proposed by ICAO (2005). According to ICAO (2005a, Doc. 9854, p. 1-1), ATM was defined as *"the dynamic, integrated management of air traffic and airspace — safely, economically and efficiently — through the provision of facilities and seamless services in collaboration with all parties".* In addition, this ConOps explicitly indicated 11 expectations (discussed among the ATM community) for the global ATM system and these expectations have been further defined as 11 KPAs in the Manual on Global Performance of the Air Navigation System (ICAO, 2009), which indicate the direction of development direction of the civil aviation up to 2025 and beyond. The 11 KPAs and their original definition refer to Appendix 1.

The definitions of the KPAs are defined based on the expectations of the ATM community regarding the future ATM system. Each of them is further instantiated by a series of Key Performance Indicators (KPIs) to quantify the operational performance, including the past, the current and the expected future performances, as well as to evaluate the actual progress of the performance objective (ICAO, 2005a). Various KPIs are identified by the SESAR and NextGen schemes. KPAs that are most relevant to airport operation and its corresponding KPIs, and that are to be adopted to validate the proposed research later, are summarised below. While safety and security - both highly important KPAs in airport operation - are not directly considered in this research, they are implicitly accounted for in this research when implementing taxiing rules and formulating microscopic simulations of airport surface movement. Table 2.1 illustrates the benefits that are expected to result from this research.

Table 2.1. IATA-IDRO operational objectives, and corresponding KPIs in terms of the main KPAs

Objective	KPA	KPI	Information
1. Minimise taxi distance	Operational Efficiency	Taxi delay	Taxi distance and taxi delay are key metrics for airport operational efficiency (Vreedenburgh, 1999). Reduced taxi distance and taxi delay therefore contribute to operational efficiency in term of fuel efficiency (fuel consumption) and time efficiency.
		Taxi distance	
	Environment		A positive relationship between taxi distance and fuel burn and emissions has been identified (De Neufville et al., 2013)
	Cost-Efficiency	Taxi time	A reduction of engine-on time contributes to lower fuel burn (cost-efficiency) and emissions (environmental impacts) (De Neufville et al., 2013).
2. Improve apron utilisation	Operational Efficiency	Gated assignment (%)	Maximising the number of gate assignments allows more aircraft to be assigned to contact stands, directly benefiting passenger service satisfaction. In addition, parking at contact stands may have a positive impact on the efficiency of the ground handling service, which has an impact on operational efficiency.
3. Minimise taxi route impedance	Operational Efficiency	Taxi time	Taxiing along the route with the least impedance results in reduced taxi time, improving operational efficiency.
		Conflicts	Taxiing along the route with the least impedance results in reduced potential conflicts.
	Safety		A significant reduction in the number of conflicts, not only enhances operational safety, but also contributes to a reduction of ATCO's workload due to reduced number of resulting interferences.
	Cost-Efficiency		A significant reduction in the number of conflicts allows aircraft to move with a reduced number of acceleration and deceleration events, reducing fuel consumption (Khadilkar and Balakrishnan 2012).
4. Improve runway utilisation	Capacity	Runway throughput	Improved runway utilisation contributes to increased runway throughput, directly benefiting capacity enhancement and improvement.
	Operational Efficiency	Runway queuing	Long runway queuing cause conflicts and congestion on the airport surface. Reducing runway queuing by improved runway assignment and reducing waiting time by improved runway throughput and off-block control, enhance operational efficiency.

2.6 SUMMARY

This chapter has introduced the airport system, by first providing a brief introduction of the airport and highlights the importance of airport operation improvement in terms of key performance for achieving a high-performing ATM system in the future. Through analysis of airport structure, airport operation as well as relevant stakeholders, it is concluded that runway-taxiway-apron are interconnected and interdependent both from the physical structures and operational processes on the airport surface. However, current operations have focused on optimising individual components of airport operation mostly in isolation, partly due to the complexity of the integrated operation and various stakeholders involved. Such lack of collaborative decision has led to under-utilisation of airport resources, and consequently causes inefficient operation. Therefore, optimisation in an integrated manner enables streamlined operations of runways, taxiways, and aprons to deliver qualified service, cost-effective management, and high utilisation of airport resources (such as stands, taxiway capacity, runway capacity). This may contribute to the goal of **full integration** of airports into the ATM system.

Given the above conclusion, Chapter 3 reviews operational concepts, technologies, and methods proposed by SESAR and NextGen for the purpose of improving operational efficiency on the airport surface, as well as academic studies in terms of individual component optimisation (i.e. runway management, taxiway operation, apron assignment) and partial integrations of these components. Chapter 3 aims at gaining a critical understanding of the state-of-the-art in terms of concepts, initiatives, technologies, and methods, and identifying critical gaps to be addressed in this research.

CHAPTER 3 STATE-OF-THE-ART OF AIRPORT SURFACE OPERATION

To address the bottleneck effect of airports in air traffic operation, many initiatives and academic studies have been undertaken to improve airport surface management, including arrival and departure management on runways, aircraft routing and scheduling on taxiways, as well as gate assignment and release. This is in addition to development of operational concepts, expansion of facilities, optimisation of procedures, and deployment of decision-support tools. These are underpinned by advanced Communication, Navigation and Surveillance (CNS) technologies (e.g. Data Communication, Performance-Based Navigation (PBN), Automatic Dependent Surveillance-Broadcast (ADS-B), System-Wide Information Management (SWIM[12])) and the Flight Management System (FMS). This chapter discusses the research into airport surface operation, including initiatives proposed in SESAR and NextGen, and related academic studies.

3.1. AIRPORT SURFACE MANAGEMENT IN SESAR AND NEXTGEN

Performance-based airport management is a pre-requisite for a future performance-based ATM system. In order to improve airport operations, SESAR and NextGen have proposed the following operational concepts: Airport Collaborative Decision Making (A-CDM), Arrival Manager (AMAN), Departure Manager (DMAN), Surface Manager (SMAN), Advanced-Surface Movement Guidance and Control System (A-SMGCS), Surface Collaborative Decision Making (Surface CDM).

[12] SWIM consists of standards, infrastructure and governance enabling the management of ATM-related information and its exchange between qualified parties via interoperable services (SJU, 2014 a&b&c&d)

3.1.1. Arrival Manager

Arrival Manager (AMAN) is an automated sequencing tools for the ATCOs to handle traffic arriving at an airport and/or to manage (or meter) the flow of aircraft entering the airspace (i.e. TMA) in an optimal sequence (Fairclough, 1999). It aims to improve the utilisation of the runway capacity by considering the airspace state, wake turbulence, aircraft capability and user preference. In addition, AMAN provides predictability for both ground and air movements, such as providing Target Landing Time (TLDT) for A-CDM. Optimised arrival sequencing has positive impacts on airport/TMA capacity and fuel burn. The reduced holding and low-level vectoring also lead to positive environmental effects in terms of noise and CO_2 emissions (EURONTRONL, 2016b; Fairclough, 1999).

Currently, the Basic AMAN provides sequencing or metering of arrivals in given TMAs and airports, as well as simple Time To Lose/Time To Gain – TTL/TTG information. Based on the information, the ATCOs consequently conduct proper approaches (e.g. vectoring, path stretching, speed changes, or holding) for the aircraft to meet their designated time or position in the sequence (EURONCONTROL, 2016b). The Basic AMAN is a baseline for establishing the (future) AMANs pro-actively by providing complex trajectory management solutions (EUROCONTROL, 2010a).

Within the A-CDM System, AMAN performs the calculation of TLDT for each arriving aircraft by taking into account various constraints and preferences (EUROCONTROL, 2015).

3.1.2. Extended Arrival Manager

Extended Arrival Manager (E-AMAN) is a concept proposed by SESAR, also featured in the Aviation System Block Upgrades (ASBU) introduced by ICAO. It allows metering of traffic into a busy TMA from far out in the en-route airspace. This concept solution is implemented based on SWIM-compliant information exchange infrastructure (SJU, 2018a, 2018b).

3.1.3. Departure Manager

Similar to AMAN, Departure Manager (DMAN) is also a sequencing tool, for improving departure flows at one or more airports by calculating the departure sequence for each departing aircraft, taking into account multiple constraints and preferences (EUROCONTROL, 2010c; Dubouchet, 1999).

In order to further improve the efficiency of the airport surface operation, the concept of DMAN within the concept of the A-CDM nowadays focuses on optimal sequencing on runways (DMAN) based on airspace state, wake turbulence, aircraft capability and user preference, and also optimises the pre-departure sequence (TSAT) at the apron. TSAT is generally to be achieved by calculating in reverse from the Calculated Take-off Time (CTOT), taking into consideration the location of the stand (gate) and the assigned departure runway, departure separation requirements and other operational constraints on the airport surface (e.g. surface network traffic flow, runway crossing) (SJU, 2018c & 2018d).

3.1.4. Pre- Departure Manager

DMAN is synchronised with Pre-Departure Manager (Pre-DMAN) to improve departure flows and departure predictability. The accuracy of the pre-departure sequence can be improved by considering dynamic data provided by A-SMGCS, including the stand location, taxi route distance, and tactical adjustments. It was proven that by using the dynamic route planning information, the predictability and stability of departure time could be improved (SJU, 2020).

3.1.5. Surface Manager

Commission Implementing Regulation (2014, No. 716, p.11) defined Surface Manager (SMAN) as "*An ATM tool that determines optimal surface movement plans (such as taxi route plans) involving the calculation and sequencing of movement events and optimising of resource usage (e.g. de-icing facilities)*". This, as a planning function, is embedded into the A-SMGCS system. Its definition suggests that the objective of SMAN is to optimise the surface movement

for each aircraft, including taxiing routing and scheduling (from aprons to runways for departing aircraft, and from runways to stands for arriving aircraft), as well as the usage of the existing resources. For taxiing planning, this is done by considering a range of constraints, such as TTOT, CTOT, Target Off-block Time (TOBT) and network traffic flow on the surface. The optimal taxiing route is consequently calculated (EUROCONTROL, 2015).

Currently, an **Automated assistance for surface movement planning and routing** is being developed by SESAR, and is to deploy across Europe. This calculates an optimum taxi route based on given stand and runway positions, as well as other operational data. The resulting route is then displayed on the controller's working position. Controllers can edit a route graphically before relaying it to pilots verbally or through datalink. This route plan can be used with other tools or systems (e.g. airport moving map, ground lighting system) to navigate pilots or vehicle drivers through the airport taxiing network.

3.1.6. Advanced-Surface Movement Guidance and Control System

Advanced-Surface Movement Guidance and Control System (A-SMGCS) is a system with four key functions, namely surveillance, guidance, control, and route planning, to support airport surface operations efficiently in all weather conditions (especially under low visibility) without compromising safety.

The implementation of A-SMGCS is planned in four levels (SJU, 2013; SJU, 2015a).

Level 1 provides improved surveillance that covers the manoeuvring area for ground vehicles and the movement area for aircraft.

Level 2 supports the guidance function based on airport static map for the operation of vehicles and aircraft, as well as safety nets function that provides conflict alerts to ATCOs on runways, including runway monitoring and alerting, ATC clearance alerting and conformance monitoring and alerting.

Level 3 provides conflict detection which extends the scope of detection from runways in level 2 to all movement area, as well as improved guidance function based on the airport dynamic map (i.e. with runway status) and planning functions.

Level 4 fully implements all functions including surveillance for controllers and all participating mobiles, conflict detection and resolution for all vehicles in the manoeuvring area and all aircraft in the movement area, automatic planning for controllers and equipped mobiles, as well as guidance through the Taxiway Centreline Lights (TCL) and the automated activation of the Advanced-Visual Docking Guidance System (A-VDGS) (SJU, 2013 & 2015a; EUROCONTROL, 2010b & 2010e & 2018; Adamson, 2006).

3.1.7. Airport Collaborative Decision-Making

Airport Collaborative Decision-Making (A-CDM) is a EUROCONTROL concept, which was developed as SESAR and the industry attempted to move toward Total Airport Management (TAM) (EUROCONTROL, 2006b, 2006c). A-CDM has been implemented in 28 airports in Europe, aiming at improving the overall efficiency of airport operation by improving the predictability of aircraft operation process and optimising the utility of existing resources. This is achieved through real time data information sharing amongst all relevant participants (see Figure 2.9) and decision-making in collaboration with others (EURONCONTROL, 2015&2017a&2017b). The main focus is on the aircraft turn-around and pre-departure sequencing process. The manual of Airport CDM Implementation, issued by Airports Council International (ACI), EUROCONTROL and IATA, highlights the A-CDM concept elements:

- Information sharing (the foundation for all the other elements);
- The milestones approach (turn-around process) (see Figure 3.1);
- Variable taxi time;
- (Collaborative) pre-departure sequencing;
- (CDM in) adverse conditions; and
- Collaborative management of flight updates.

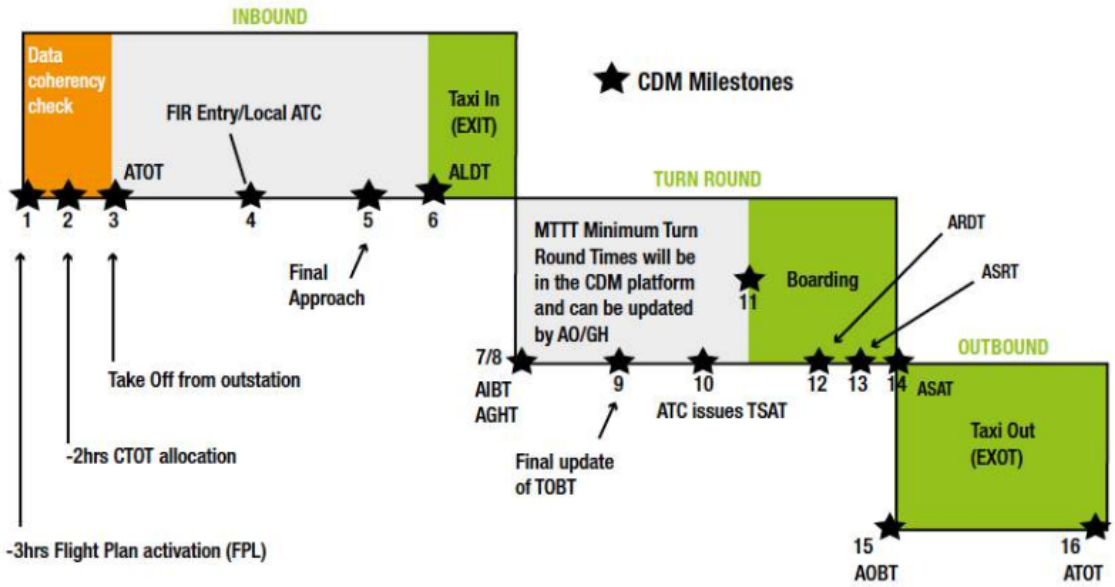

Figure 3.1. The A-CDM Milestones（EUROCONTROL, 2015）

Each element will only work properly in conjunction with all preceding elements. The expected benefits of A-CDM are derived from information sharing and updating as well as collaborative decision-making, because all relevant participants contribute to increased predictability. The great benefits for CDM airports are shown in Figure 3.2 (EUROCONTROL, 2015).

Through the implementation of the A-CDM in airports, 7% of taxi time and 9.8% of ATFM delays have been reduced across at CDM airports, and subsequent savings in tactical delay costs reached to approximately 1 million Euros in 2015 (EUROCONTROL, 2017b).

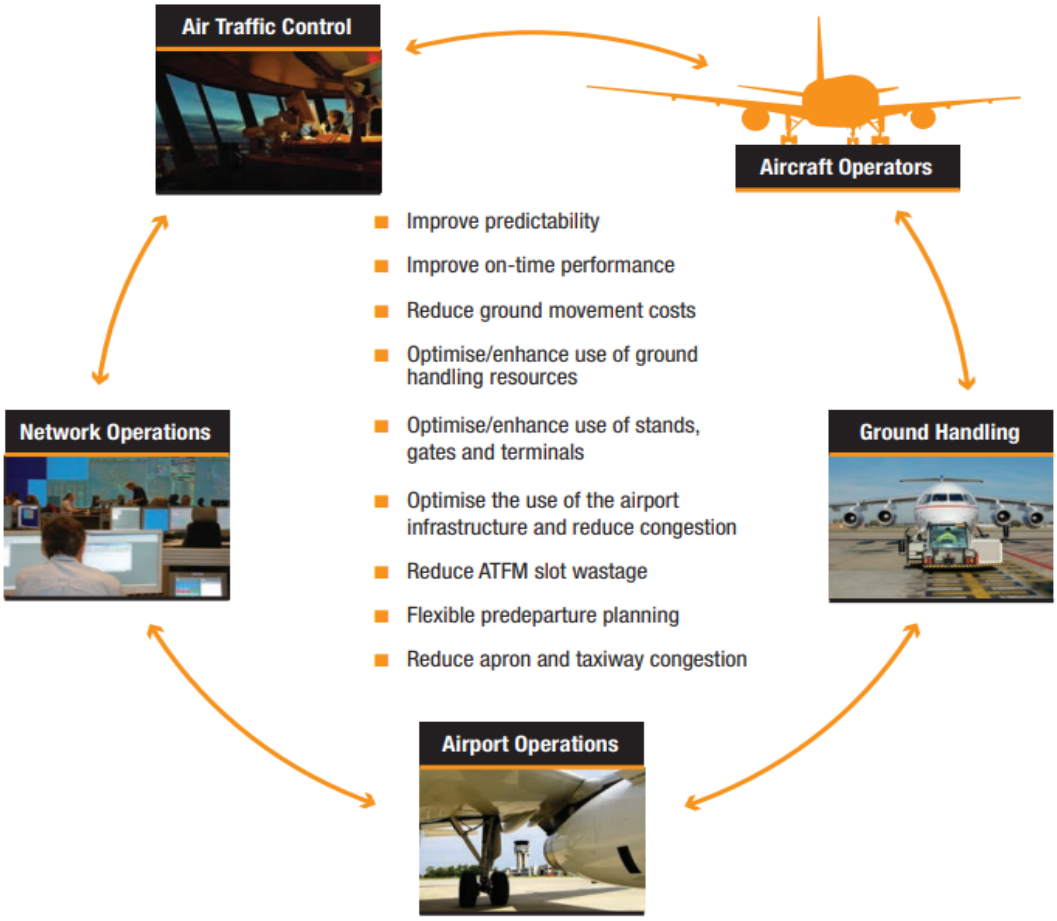

Figure 3.2. The A-CDM stakeholders and objectives (EUROCONTROL, 2015)

3.1.8. Surface Collaborative Decision-Making

In the USA, Surface Collaborative Decision Making (S-CDM) ConOps was proposed by FAA, providing the safe and efficient management of traffic flow on the airport surface, decreasing uncertainty and increasing predictability of demands at U.S. airports. This could be achieved through accurate and real time information sharing and data exchange, as well as by collaborative decision-making amongst all stakeholders (i.e. airport, ATC, airlines) (FAA, 2012a). Within the Surface CDM, the two most important elements in the system are the Earliest Off Block Time (EOBT) and the Target Movement Area Time (TMAT). EOBT is

essential for the S-CDM system, as airlines must determine or update EOBT and to notify the system through EOBT if an aircraft is expected to be delayed or the flight cancelled. An aircraft is expected to enter the taxiway/movement area within its assigned TMAT slot (defined to be TMAT plus/minus 5 minutes).

The implementation of ConOps will not only improve the safety and efficiency of the surface operation locally (at local airports) and regionally (the participant airports), but also facilitate the future interoperability among regions (i.e. A-CDM in Europe). Airport (Surface) CDM ConOps and further integration among a wider range of systems with different regions (i.e. Europe, US, China, and even the whole world) lay the foundation for an integrated, harmonised and globally interoperable ATM system.

Table 3.1 provides a comparison of the aforementioned operational concepts with the IRTA proposed in this research, in terms of KPAs (ICAO, 2005a) and key functions. The coordination of AMAN, DMAN, SMAN, A-CDM (on an information sharing platform) is illustrated in

Figure 3.3, where AMAN and DMAN perform runway sequencing leading to ELDT and TTOT, respectively, while SMAN and A-SMGCS based on the information of runway and stand positions, as well as other data, determines taxi routing during in-bound and out-bound phases, respectively.

Table 3.1. Comparison of the operational concepts

		AMAN	**(Pre-**	**A-SMGCS**	**SMAN**	**A-CDM**	**IARA-IDRO**
KPAs	Cost-efficiency	✓	✓	✓	✓	✓	✓
	Predictability	✓	✓	✓	✓	✓	✓
	Capacity	✓	✓	✓	✓	✓	✓
	Safety	✓	✓	✓	✓	✓	✓
	Efficiency	✓	✓	✓	✓	✓	✓
Functions	Runway operation	✓	✓	×	×	×	✓
	Taxiing routing	×	×	✓ (future)	✓	×	✓
	Gate release	×	✓	✓	✓	×	✓
	Gate assignment	×	×	×	×	×	✓

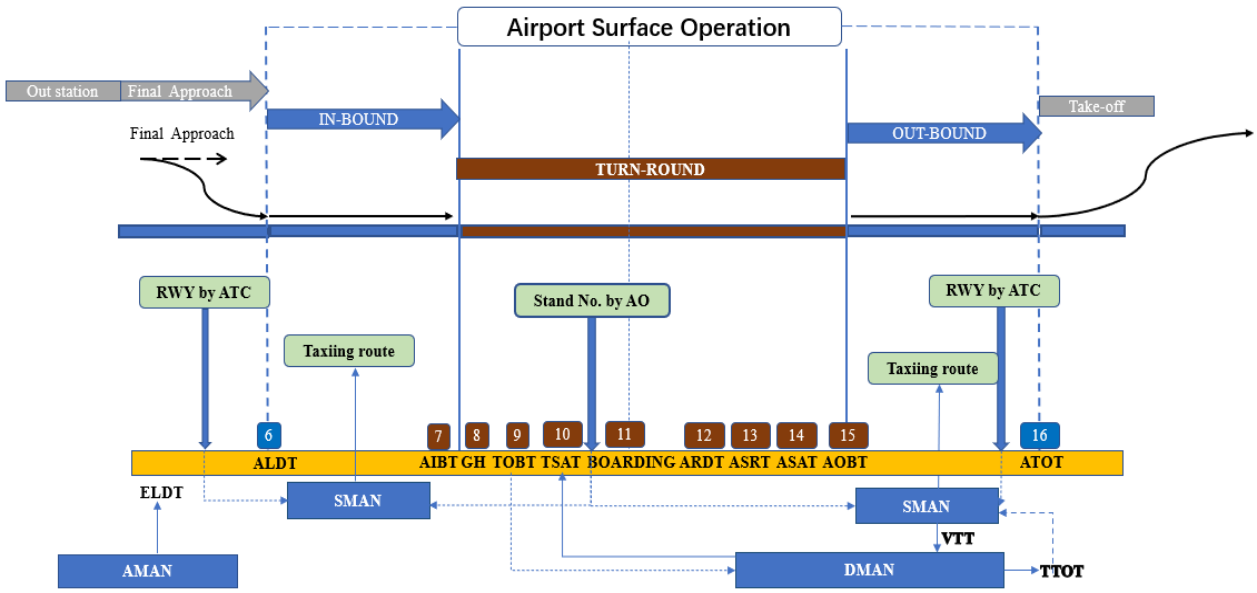

Figure 3.3. Collaboration of AMAN, DMAN, SMAN within A-CDM

3.1.9. Other Enhanced Airport Operation Solutions in SESAR

The future ATM system relies on full integration of airports as nodes in a network, in addition to the assistance tools and procedures introduced above, as well as other advanced technologies and solutions focusing on the surface movement and airport operation, which have been developed and deployed in SESAR, with the objective of enhancing airport operation performance in terms of capacity, predictability, efficiency, environmental impact and safety. These additional tools and solutions are briefly introduced below.

3.1.9.1 Enhanced runway throughput based on advanced systems

Increased runway throughput crucial to improving the performance of airport surface operations in terms of operational efficiency, cost-efficiency, environmental impact, and capacity.

- **Satellite-based Navigation Systems** (e.g. GBAS and SBAS) are employed to enhance landing performance and to facilitate advanced arrival procedures, such as curved approaches, glide slope increase, and the displaced runway threshold. In addition, the operational combination of enhanced navigation capability provided by augmented satellite signals flown by equipped traffic, with a glideslope leading to a further runway aiming point, also enhances runway capacity and throughput.
- **Time-Based Separation (TBS)** aims at reducing the gap in landing rates in light or strong headwind conditions. Depending on the wind condition, if arriving aircraft are separated by required time minima while landing, instead of applying distance separation, the resilience of runway throughput and efficiency can be consequently increased.
- **Separation Optimisation (RECAT-EU)** in Europe redefines the Wake Vortex of aircraft into six categories: Super Heavy (A), Upper Heavy (B), Lower Heavy (C), Upper Medium (D), Lower Medium (E), Light (F). This system is, in contrast to the three Maximum Take-off Weights (MTOW) (Heavy, Medium, Light), currently defined by ICAO. This precise separation strategy avoids excessive separation in some instances, and the reduced RECAT spacing between arriving aircraft contributes to increased runway throughput, as well as to reduced fuel burn and emissions, and operational cost reduction due to reduced flight time. Now the SESAR programme has been further studying on RECAT-2 (pair-wise separations), RECAT-3 (dynamic pair-wise separations) and weather dependent separations (WDS).

3.1.9.2 Situation awareness tools and systems

In addition to decision-making tools to improve airport surface operation, increased situational awareness is also important to ensure safety and maintain operational efficiency in all weather condition on the airport surface.

- **D-TAXI** is an application of **controller-pilot datalink communications (CPDLC)** for taxiing while the information and clearances are delivered by datalink. This solution

improves communication between controllers and flight crew by using datalink to exchange messages and information, such as routine exchanges in pre-departure periods, pushback clearance, start-up and taxi instructions, as well as other information (e.g. revised taxiing instruction or the de-icing procedure);

- **Guidance System** (Follow-the-Greens) makes use of taxiway centre lights, by linking with the taxi route management system, to provide aircraft and vehicles a route to follow (European Commission, 2017； Biella et al., 2015; Fines et al., 2020).
- **Electronic Route Plan** selects the most suitable route from the gate to the runway and vice versa delivering automated assistance to controllers for movement planning and routing. This plan can be shared with not only the pilot, but also other related operators (e.g. the airline operation centre, and controllers). This electronic route plan may also be used with enhanced guidance assistance tools, such as airport moving maps in aircraft or the ground lighting system, to provide guidance instructions.
- **Virtual Stop Bars** allow controllers to reduce the size of the control blocks used in low visibility conditions to maintain safe separation distances between taxiing aircraft and reduce the risk of runway incursions (ACI, 2014; SJU, 2017a).
- **The Taxi Route Display for Pilots** provides graphical display instructions for taxiing instruction, which can increase the flight crew's situational awareness. For example, flight crew can check whether they are following the correct route received from the ATCOs. In addition, the taxi route can be overlaid on the moving map, so that the pilot can see the exact location of the aircraft in relation to the cleared route. Furthermore, the taxi route may be relayed to the pilot using CPDLC, and may be linked with airport safety nets to alert the pilot of potential hazards, particularly during low-visibility conditions or at night.

3.1.9.3 Airport safety nets

SESAR has deployed the following measures to enhance safety and reduce risks.

- **Airport safety nets** for controllers, which provide conformance monitoring alerts (e.g. aircraft or vehicle does not comply with ATC instructions) and detection of conflicting ATC clearances (e.g. clearances for line up and landing given simultaneously).
- **Safety nets for vehicle drivers** provide vehicle drivers with an enhanced visual tool (i.e. a screen display) enabling access to a dynamic map with information displayed about nearby traffic, and sending alerts or warnings about potential conflicts or dangers.
- **Runway Status Lights (RWSL)** includes three types of LED lights: Runway Entrance Lights (RELs), Take-off Hold Lights (THLs), and Runway Intersection Lights (RILs), providing instant visual alerts for the pilot or vehicle driver on the airport surface, aiming at reducing the number and severity of runway incursions (ACI, 2014).
- **Further ADS-B** has a safety-warning function that provides alerts about major conflicts in all weather conditions.

3.1.9.4 Total Airport Management

Timely information sharing among all stakeholders is of crucial importance for the coordination of various operational functions and full integration into the ATM system (EUROCONTROL, 2006c). Therefore, the concept of the Total Airport Management (TAM) was created to provide a full knowledge of airline operational constraints and/or priorities amongst all stakeholders through information sharing in a timely manner between individual Airport Operation Plans (AOPs) and Network Operation Plan (NOP) using SWIM technology. It supplements the proposed concept of A-CDM, AMAN, DMAN, A-SMGCS, which exclusively plan and execute trajectory information within the airport airside, while ignoring the landside trajectory (e.g. check-in, security, boarding) (Günther et al., 2006, TAMS Partners, 2012). The core information of the TAM is the AOP, which is a subset of the NOP and is

updated from a strategic, pre-tactical phase of operations to tactical phase of operations (SJU, 2017b; European Commission, 2016).

In addition to the aforementioned advanced procedures, assistance tools, and improved infrastructures at major airports, SESAR and NextGen also focus on the management of secondary airports with limited resources to invest in advanced ground infrastructure. The solutions include **enhanced accessibility** technology by means of Enhanced Vision System (EVS) and Synthetic Vision Systems (SVS) for taxiing and take-off in low-visibility conditions. **Remote Tower** provides air traffic control services in a cost-efficient manner to small, secondary, or non-towered airports, and provide backup remotely for contingency situations at aerodromes. It is said that the London City Airport is the first international airport in the world to be completely controlled by a virtual system at NATS' air traffic control centre in Swanwick, Hampshire, UK (Online News, 2021).

NextGen represents an evolution from a ground-based system of ATC to a satellite-based system of ATM. The NextGen programme, in terms of procedures and technologies, involves Automatic Dependent Surveillance Broadcast (ADS-B), System-Wide Information Management (SWIM), NextGen Data Communications, NextGen Network Enabled Weather (NNEW), NAS Voice Switch (NVS) and NextGen Demonstrations and Infrastructure Development.

3.2. OPTIMISATION OF AIRPORT SURFACE OPERATIONS

Aside from the aforementioned operational concepts, new technologies and procedures proposed by SESAR and NextGen to enhance airport performance, a large number of academic studies have been focusing on airport operational performance based on the utilisation of existing infrastructures (runways, taxiways, and aprons). This section categorises and compares existing research in terms of improvement of airport surface operation including single component optimisation and various integrated operations. This initial focus is on objectives (Section 3.2.1) and methodology (Section 3.2.2) before reviewing relevant studies that address isolated (Section 3.2.4) and integrated (Section 3.2.5) operations.

3.2.1. Research Objectives

In terms of objectives to be improved or optimised, due to the increasing demand of aircraft, airports are considered as "bottlenecks" in terms of capacity, operational efficiency, and environmental impact. To enhance airport surface operations, existing studies have focused on runway throughput and time-efficiency related objectives; these include taxi time, taxi delay, and deviations of Central Flow Management Unit (CFMU) . Moreover, the sustainability aspect of ATM has been accounted for by considering various environmental objectives such as fuel burn and emissions of greenhouse gases and other pollutants during the taxiing process.

3.2.1.1. Operational efficiency

A large body of academic studies has focused on minimising the total taxi time or/and taxi delays to improve airport operational efficiency in terms of time-efficiency and cost-effectiveness. Bosson et al. (2015) proposed a fast decision support algorithm with the objective of minimising the total travel time including taxiing time on the surface and flying time in the airspace terminal. Guepet et al. (2017) conducted an integrated optimisation of the taxiing schedule and runway sequence, by minimising the total taxiing time and competition time. This research was based on a predefined taxi route between a given O-D pair. Wang (2014) attempted simultaneous minimisation of the taxi time and maximisation of runway throughput,

by selecting appropriate taxiing routes and schedules, as well as runway sequencing. Benic et al. (2016) proposed a heuristic search method to optimise runway sequencing and taxiway routing. Their research focused on minimising the sequencing and taxiing delay, which were considered as primary and secondary objectives, respectively. Pavese et al. (2017) adopted a mixed integer linear programming approach to integrate the use of AMAN, DMAN and SMAN at Linate airport, aiming at improving the efficiency of the airport surface operation in terms of mean taxi delay and mean taxi time. Other similar research in this regard includes that done by Herrero et al. (2005).

In addition, studies have been focusing on minimising taxi time and/or delay, along with other objectives including waiting times at nodes during the taxiing phase (Ravizza et al., 2013a), taxi distance or long taxi route (Keith et al., 2008; Clare et al., 2009; Clare and Richards, 2011), deviation from the CFMU (Gotteland et al., 2001; Balakrishnan and Chandran, 2010; Lee and Balakrishnan, 2012) or from scheduled times of departure/arrival (STD/STA) (Smeltink and Soomer, 2004; Balakrishnan and Jung, 2007; Deau et al., 2008). In particular, a weighted combination of makespan, the average taxi time, and the average taxi distance was minimised by Keith and Richards (2008).

3.2.1.2. Capacity assessment and enhancement

Accurate assessment of capacity is of great importance to airport operational management. Over-estimating runway capacity can lead to excessive flight scheduling and frequent ad-hoc adjustment, which would result in long queues and delays, reduced service quality, and even potential safety issues due to inadequate airport resources. On the other hand, underestimation of the airport capacity would impose significant but necessary constraints on flight scheduling and cause under-utilisation of existing resources. Therefore, EUROCONTROL and FAA have published a series of airport capacity assessment criteria and enhancement planning documents. For example, detailed planning guidelines for future airport capacity assessment techniques, capacity requirements, and capacity improvement measures can be found in FAA (1968), FAA (1982), FAA (1987), FAA (1989), and FAA (1983). EUROCONTROL has also issued a series

of documents including Guidelines on Runway Capacity enhancement (EUROCONTROL, 2001), Airside Capacity Enhancement (EUROCONTROL, 2003), Safety Assessment of Airport Airside Capacity Enhancement (EUROCONTROL, 2006a), Capacity Planning Guidance & Assessment (EUROCONTROL, 2007&2008&2009), Capacity Assessment and Planning Guidance document (EUROCONTROL, 2013b), and Airport Capacity Assessment Methodology (EUROCONTROL, 2016a).

In addition to the guidelines issued by FAA and EUROCONTROL, earlier academic studies have focused on evaluating runway capacity (throughput), in terms of runway departure capacity (Simpson et al., 1986; Blumstein,1959) and runway capacity under mixed modes (Jiang et al., 2003). Definition of runway capacity has been proposed by categorising it into theoretical, actual, operating and planned capacities (Zhu, 1998). Other runway capacity assessment methods that analyse a series of factors can be found in (Harris, 1972; Lee et al., 1998; Cetek et al., 2014; Chen, 2007).

Furthermore, because of limited airport and airspace terminal resources, the relationship between departures and arrivals in relation to runway capacity has been widely studied. Newell (1979) illustrated the interdependency between arrival and departure rates on runways through a convex and nonlinear functional relationship. A more specific relationship for a given airport runway, known as the capacity envelope, was proposed by Gilbo (1993) based on a combination of mathematical model using empirical data, and it was validated by air traffic managers and controllers. Further development on the capacity envelope can be found in (Gilbo and Howard, 2000; Barrer et al., 2005; Gluchshenko, 2012).

3.2.1.3. Environmental impacts

Developing sustainable ATM system is one of the key targets in the SESAR Master Plan (European Commission, 2015). Previous studies focused on minimising the total taxiing time or the engine running time, under the premise that emission and fuel consumption are positively correlated to these factors (Balakrishnan and Jung, 2007; Roling and Visser, 2008; Gotteland

et al., 2001). However, recent research has shown that this is not always the case, and that there exists a potential trade-off between taxiing time and fuel consumption (Chen and Stewart, 2011; Ravizza et al.,2013b). Furthermore, Khadilkar and Balakrishnan (2012) showed that the number of acceleration events is a significant factor in fuel consumption. Meanwhile, the states of idling and taxiing at constant speed or braking were found to be the two most significant situations affecting fuel burn and emissions, and this has been confirmed at Dallas-Fort Worth International Airport (Nikoleris et al., 2011). In response to this, a weighted objective was applied to solve ground movement problem (Chen et al., 2011&2015b&2016; Ravizza et al., 2013b; Weiszer et al., 2014, 2015a, 2018) due to the potential trade-off between taxi time and fuel burn (Ravizza et al., 2013b).

An alternative approach for reducing fuel burns and emissions during taxiing process on the airport surface was based on Single-engine Taxiing (SET), which allows pilots to switch off one (for a two-engine aircraft) or two (for a four-engine aircraft) engine(s) during taxiing process (EUROCONTROL, 2019; Stettler et al., 2018). The effectiveness of SET, in terms of fuel burns and emissions can be found in Guo et al. (2014), which showed reduction of up to 50% in both fuel burns and NOx emissions, and this has been verified in ten of the busiest airports in the U.S. Similar research in terms of SET to reduce fuel burns and emissions can be found in (Kumar et al., 2008; Deonanda and Balakrishnan, 2010). However, all the aforementioned studies were based on an assumed 7% taxi thrust setting for the operating engine(s), while the other engine(s) were switched off during the taxiing procedure. Such an assumption stems from the lack of high-resolution aircraft trajectory data encompassing SET activities. In light of this, Stettler et al. (2018) developed a more realistic emission model for SET using 3510 empirical trajectory data records of London Heathrow Airport. The results show that fuel burns and emissions would increase by up to 50% without SET during taxiing-in stage. This method holds promise of more accurate calculations of fuel consumptions and emissions. However, the adoption of SET might not reduce fuel burns and emissions in airports suffering from congestions, where stop-and-go movement, excessive runway queuing and even

gridlock are common. Moreover, SET so far has not been widely accepted by all airports and airlines.

3.2.2. Research Methodology

Methodologies for improving airport surface operations include quantitative and qualitative research methods or a combination of the two. There are advantages and disadvantages of each method; selecting the most appropriate research methodology, depending on identifying the research question and the desired outcome of the study has an important impact on the feasibility and effectiveness of the research (Shorten and Smith, 2017).

3.2.2.1. Quantitative method

A quantitative method including **mathematical research** and **simulation model,** has been widely used in the current literature on airport surface optimisation. Mathematical research includes **exact methods** -- such as Linear Programming (LP), Mixed Integer Linear Programming (MILP), Integer Programming (IP) and Integer Linear Programming (ILP) -- which can find a global optimum following a specific iterative procedure with provable convergence. Relevant research can be found in (Atkin,2010; Roling and Visser, 2008; Smeltink et al., 2004; Rathinam et al., 2008; Marin, 2006; Marin and Codina, 2008; Clare and Richards, 2011; Wang et al., 2014; Bosson, 2015; Bertsimas and Frankovich, 2016; Pavese et al., 2017; Bertsimas and Frankovich, 2013). Compared with the exact methods, the **heuristic methods** are customised algorithms that are capable of searching for a near-optimal solution within limited computational times or numbers of iterations. In practice, it is difficult for these algorithms to find a globally optimal solution as the result often settles on local minima or maxima. Heuristics are most likely to be adopted to solve complex problems that are otherwise impractical to solve with exact methods. Examples of the application of heuristics can be found in ground movement operations (Ravizza et al., 2013a; Weiszer et al., 2014; Weiszer et al., 2015a&b; Benlic, et al., 2016; Guépet et al., 2017; and Atkins et al., 2004). Meanwhile,

compared with heuristic methods, **metaheuristic algorithms**, such as Tabu research, Genetic Algorithms (GA), and simulated annealing algorithm, apply various sophisticated mechanisms to avoid local optimal solutions, or to escape from a local optimum in search of global ones.

On the other hand, a **simulation** can describe the operation of a real-world system or process over time and can provide measurable values for several KPIs and proof for the development of a proposed concept. This is a popular method for validating a design or concept or to predict behaviour in certain real-life situations. In the simulation model, the key issues include the acquisition of valid data and key characteristics, the use of simplified approximation, and proposed assumptions, to guarantee the fidelity and validity of the simulation outcomes (Kamat and Martine, 2003). Examples can be found in the accounts of commercial simulators, TAAM, SIMMOD, AnyLogic and AirTOp, which have been used in academic and industrial research to simulate airport operations. These commercial simulators offer various degrees of convenience but increase uncertainties and randomness since the inherent algorithms are unknown. For example, when the runway and gate are assigned to an arriving aircraft, as an intelligent agent the aircraft chooses the most efficient taxiing route, which is not always in line with the real-world taxiing rule. Another line of simulation practice involves explicit modelling of aircraft movement with varying granularities, including macroscopic models (i.e. queuing network and the Macroscopic Fundamental Diagram), mesoscopic models (i.e. Cell Transmission Model) and microscopic models (Cellular Automata), with the benefits of customized algorithms, transparent procedures, efficient computations, and low costs compared to commercial simulators, (Yang et al., 2017; Sanchez, 2019; Yin et al., 2022, Simaiakis and Balakrishnan, 2016; and Mazur and Schreckenberg, 2018).

3.2.2.2. Qualitative method

A qualitative method -- based on observation, interviews, surveys, questionnaires, and focus group meetings -- is a non-numerical approach, which uses as a benchmark performance and safety criteria according to ICAO Standards (Shortle, 2006; Shyur, 2008; Puranik, 2018; Studic, 2015; and Merkisz-Guranowska, 2016). In the current literature on existing

optimisation research, the quantitative method is normally used in a mixed methods approach together with a quantitative method, to provide useful information for the design and selection of the appropriate qualitative method.

3.2.2.3. A mixed methods approach

A mixed approach allows a more comprehensive understanding of connections or contradictions between qualitative and quantitative approaches. Therefore, it is of importance for data linkage and integration at an appropriate stage in the entire research process (shorten and Smith, 2017). A combination of quantitative and qualitative approaches was adopted to validate the accuracy and effectiveness of the proposed dynamic route concept, as well as for the sake of safety in (Sidiropoulos, 2016; Sidiropoulos et al., 2015a&2015b&2018), when designing a dynamic route to improve operational efficiency for Multi-Airport Systems (MAS) terminals. Alers (2013) adopted a qualitative method which involved interviewing various stakeholders to obtain all possible options when optimising airport passenger terminal operations. Based on the results of the interviews, a quantitative method was used to rank and evaluate the optimisation solutions. Musa and Lsha (2021) proposed integration of qualitative and quantitative methods with data triangulation to provide a holistic view of safety culture in aircraft ground handling in the airport apron area. Yin et al (2022) proposed a joint apron and runway assignment for airport surface operations based on qualitative data (i.e., interviews with subject matter experts) and quantitative data (i.e., real-world historical data) by considering the operational rules, constraints and preferences to improve the operational efficiency on the airport surface. Moreover, the optimisation results and their potential implementation were also evaluated quantitatively and qualitatively.

Moreover, to assess the validity and effectiveness of a proposed concept or design, a **case study** method using real-world data is commonly applied to the results of theoretical research or/and simulation modelling, with either a single case (Kim, 2010&2013; Cheng et al., 2012; Deau, et al., 2008; Weiszer et al., 2014; Weiszer et al., 2015b; Yang et al., 2017; Pavese et al., 2017;

and Yin et al., 2022) or multiple cases (Phillips et al., 2010; Weiszer et al., 2018; Kratudnak and Tippayawong, 2018; Kjenstad, D., 2013).

3.2.3. Airport Surface Congestion Management Strategy

The aim of Airport Surface Congestion Management (ASCM) is to improve the management capability and guarantee the fluidity of taxiing traffic in the presence of a complex airport surface layout and an uncertain operational environment. This is to be achieved by maintaining the number of moving aircraft at a critical value within a given area, corresponding to different operational scenarios through dynamically analysing traffic flow characteristics in the airport airside. The strategies include Pushback Control (Off-block Control), Spot and Runway Departure Advisor (SARDA), and Collaborative Departure Queue Management (CDQM).

3.2.3.1. Pushback control

Pushback control, also known as off-block control is a congestion mitigation strategy for controlling the off-block rates of departing aircraft, to reduce taxing time, conflicts and runway queuing during the departure process. This control method has been implemented in Boston Logan International Airport (Simaiakis et al., 2014). This field trial, splitting into eight four-hour sub-tests, has successfully demonstrated its efficiency in terms of fuel saving and taxiing time reduction. However, the characteristics of traffic flow were simplified by using historical data without considering the impact of arrivals and their uncertainties, which should clearly have an influence on surface movements. Motivated by this gap, a more sophisticated modelling approach was introduced by Yang et al. (2017), where the characteristics of traffic flow at the surface network were revealed by the macroscopic fundamental diagram (MFD). In addition, a mesoscopic dynamic model for airport surface networks was proposed based on the cell transmission model, which is capable of capturing the network-wide propagation of flow and congestions. Finally, several robust off-block control strategies were proposed based on the MFD by controlling the off-block rate for departures, in order to maintain the optimal

number of aircraft on the taxiways. This method has been applied in one of the busiest airports in China, Guangzhou Baiyun International Airport, and has shown that the proposed robust control strategies outperform existing ones in terms of reducing departure delays and runway queuing in a variety of uncertain situations.

3.2.3.2. Spot and Runway Departure Advisor

The Spot and Runway Departure Advisor (SARDA) concept was proposed by NASA to improve the efficiency on the airport surface by reducing taxi delay, fuel consumption and emissions. This was achieved by planning a detailed trajectory for each aircraft movement (gate, ramp, taxiway, and runways) at the systemic level through collaboration between ATC, airlines and en-route facilities, and then delivering two schedulers, namely an optimal runway scheduling and release sequence and timing on the spot (the hand-off points between the ground control and tower control), as well as gate release time (Calculated Take-Off Time-Estimated Taxi Time). However, SARDA focuses on the optimisation of scheduling rather than surface resource allocation (i.e. gate and runway assignment). SARDA was tested at the Future Flights Central (FFC) based on the Dallas-Fort Worth Airport (DFW). The result showed that the taxiing delay was significantly reduced by 45% in medium and 60% in heavy congestion levels while the corresponding total fuel burns have been reduced by 23% in the medium and 33% in the heavy congestion levels with the use of SARDA (Jung, 2019).

3.2.3.3. Collaborative Departure Queue Management

Collaborative Departure Queue Management (CDQM) is intended to maintain the runway for maximum usage without causing extensive delays at runway thresholds. This was achieved by allocating and controlling time slot for each departing aircraft to taxi in the movement area. The assignment of the slot was conducted through a “ration by schedule” (first scheduled first served) approach (Brinton et al., 2011). The approach was tested at MEM in 2010 and it enabled a reduction of excessive taxiing time that was estimated at 86,000 minutes, thereby

contributing to the reduction of 2.1 million Pounds of fuel burns and 6.7 million pounds of CO_2 emissions.

In addition to the integrated optimisation at the airport surface, some research extends to include the TMA by considering the interconnection of the configuration and interdependency of operation. Ma et al. (2016) and Ma (2018) attempt to optimise ground movement and TMA simultaneously on a macroscopic level, modelling each airside components (taxiway area, runway area, and TMA) have been modelled using network abstraction. The number of aircraft within each component are controlled by adjusting arrival and departure times for each aircraft. This experiment has been applied to Paris Charles De-Gaulle airport and suggest that the congestion and conflict can be reduced at both the airport surface and TMA.

3.2.3.4. Demand and capacity balance

The high degree of flight delays is created by the imbalance of air traffic demands and airport capacity at high-density airports. In general, airport congestion can be mitigated through scheduling intervention and capacity utilisation. Jacquillat and Odoni (2015) proposed an iterative solution algorithm that jointly optimises the flight rescheduling and capacity utilisation. This is done by integrating a stochastic queuing model of airport congestion, a dynamic model of capacity utilisation, the balance of arrival and departure rates and a flight scheduling module. The result was applied to the JFK airport and this revealed that the arrival and departure delays can be reduced by 20%–40% and 40%–60%, respectively in peak hours. Afterwards, Jacquillat et al. (2017) developed an effective decision-making framework to minimise airport congestion costs through dynamically controlling runway configurations and the arrival and departure rates in situations of uncertainty such as dynamic stochastic queuing and stochastic operational conditions (weather or wind-related uncertainty). This model is formulated as Dynamic Programming, and can be also used to improve the predictive ability of queuing models of airport congestions proposed by Jacquillat and Odoni (2015).

The above research offers new insights into mitigating airport congestion by metering airport demand considering the runway configurations and the balance between arrivals and departures. However, the capacity envelope was still generated in a conventional way, where flight delays did not account for arrival and departure rates simultaneously. Moreover, regarding airport congestion control, these studies took a macroscopic modelling and management point of view without detailed consideration of specific taxiing procedure.

3.2.4. Resource Utilisation in Isolation

This section reviews relevant studies on airport surface optimisation in terms of runway operation management (Section 3.2.4.1), stand (gate) assignment (Section 3.2.4.2), and taxiway management (Section 3.2.4.3).

3.2.4.1 Runway operation management

Runways which connect the airport airside to the TMA, are considered main bottlenecks of an airport. For this reason, runway throughput is the main metric to consider when assessing airport capacity. This subsection summarises existing research into capacity assessment and optimisation methods for runways.

1) Runway capacity analysis

Bowen et al. (1948) and Blumstein (1959) were among the first to study runway landing capacity, followed by scholars who conducted comprehensive studies on departure capacity (Simpson et al., 1986) and runway capacity under mixed modes (Jiang et al., 2003). To explore the potential of runway operational capability, Blumstein (1960) proposed the concept of extreme capacity, which is defined as the maximum number of aircraft that can be served within a certain period under continuous service requests. Having realised that runway capacity is highly depended on a series of factors, Harris (1972) analysed a set of factors affecting runway capacity, such as runway configurations, control system precision, and changes in aircraft

separation standard. Based on this, Zhu (1998) and Hu et al. (2000) refined the definition of runway capacity by categorising it into theoretical capacity, actual capacity, operating capacity and planned capacity. Lee et al. (1998) proposed a capacity and delay model, which was applied to more than ten airports in the US. Cetek et al. (2014) and Chen (2007) studied the relationship between airport runway capacity and flight delays. The variations in runway capacity under different weather conditions, using short-term deterministic weather models and long-term probabilistic weather models, were considered by Krozel et al. (2008) and Kicinger et al. (2012).

Due to the limited airport and airspace terminal resources, the competitive relationship between departures and arrivals in relation to runway capacity was widely studied. Newell (1979) illustrated the interdependency between arrival and departure rates on runways through a convex and nonlinear functional relationship. A more specific relationship for a given airport runway, known as the capacity envelope, was proposed by Gilbo et al. (1993), through a combination of mathematical modelling using empirical data, and validation by air traffic managers and controllers. Further development on the capacity envelope can be found in (Gilbo and Howard, 2000; Barrer et al., 2005; Gluchshenko, 2012).

2) Runway sequence optimisation

Runway sequence optimisation is one of the main techniques for improving the efficiency of landing and take-off, by delivering optimal sequencing of arrivals and departures as well as resource assignment on the surface. This is done by considering the traffic flow characteristics, airport and airspace terminal configurations and their operational conditions. Existing research covers the arrival sequence optimisation (Milan, 1997; Robinson et al., 1997; Saraf and Slater, 2006), departure sequence optimisation (Bolender et al., 2000a; Bolender, 2000b; Keith et al., 2008; Clare et al., 2009), and coordinated arrival and departure sequence optimisation (Smith et al., 1998; Bennell et al., 2011). The sequencing for single-runway (Gupta et al., 2011; Furini et al., 2012) and multi-runway (Brinton et al., 2011) systems also fall within the purview of runway scheduling. Moreover, some studies have made extensions from single airports (Atkin

et al., 2013; Zhang and Wang, 2004; Ying et al., 2011) to multi-airport systems (Qiu, 2012; Ma et al., 2015).

3.2.4.2 Airport gate assignment

The stands (or gates) on the apron serve as the destination for arrivals and origins for departures on the airport surface, which makes them a critical component of airport surface movement management and aircraft taxiing planning. As key stakeholders of airport surface operation, passengers have been highlighted and given priority in the earlier work of gate assignment. Indeed, they mainly focused on minimising total passenger walking distances or times inside the airport terminal (Bihr, 1990; Bandara, 1992; Haghani and Chen, 1998). Braaksma et al. (1977) considered various types of passengers, such as arrivals, departures, domestic, international, and transferring, with the objective of reducing total walking distance, based on the physical layout of the airport terminal. Babić et al. (1984) and Mangoubi et al. (1985) aimed to minimise the average travelling distance of passengers. Regarding solution algorithms, a branch and bound algorithm was used in Babić et al. (1984) to solve the proposed Integer Programming (IP) problem, while a linear programming relaxation of the IP formulation with greedy heuristic algorithm was used in Mangoubi et al. (1985).

Besides walking time or distance, other objectives have also been considered in previous studies. Ding et al. (2005) considered the availability of gates in their multi-objective model to minimise the total number of delayed flights caused by an insufficient number of gates, as well as the distance walked by passengers. Maharjan et al. (2011) developed a gate re-assignment model in response to flight delays to minimise the total walking time of connecting and original flight passengers. Zhang and Klabjan (2017) proposed an efficient gate re-assignment method to address disruptions, in which the objective function is to minimise the weighted sum of total flight delays, the number of gate re-assignment operations and the number of missed passenger connections. Kim et al. (2010&2013) was among the first to take ramp congestions into account when minimising passenger transit time and aircraft taxi time.

Due to the uncertainties in airport operation, Robust Airport Gate Assignment (RAGA) was first proposed by Lim and Wang (2005). Yan and Tang (2007) developed a heuristic approach embedded in a framework with three components, a stochastic gate assignment model, a real-time assignment rule, and two penalty adjustment methods considering stochastic flight delays. Yu et al. (2016) used mixed-integer programming-based heuristics, considering three significant impact factors: schedule robustness, towing costs, and passenger satisfaction. In this reserach, the robustness is measured by the expected total gate blockage time, which was also the case in Castaing et al. (2016) where a network flow-based model was proposed to resolve the RAGA problem. Dorndorf et al. (2008) modelled the robust flight gate assignment as a Clique Partition Problem (CPP). Based on this work, Dorndorf (2012) further considered a maximisation of the total assignment preference score, a minimal number of unassigned flights during overload periods, a minimisation of the number of tows, and a maximisation of a robustness measure as well as minimal deviation from a given reference schedule. In the following work, Dorndorf et al. (2017) considered both flight gate assignment and recovery strategies with stochastic arrival and departure times.

3.2.4.3 Taxiing management

The taxiway network, which connects the aprons and runways, is the largest component of airport surface area in terms of spatial extent, especially in mega airports. The aim of taxiing planning is to determine an optimal taxi route and proper release time for an aircraft while moving between the apron and the runway. Existing studies on this subject have mainly focused on taxiing time prediction, taxiing routing and scheduling, and taxi sequencing optimisation at nodes. The expected benefits in terms of KPAs involves time efficiency, cost effectiveness and environmental impact.

1) Taxiing time prediction

Accurate taxiing time prediction is crucial for estimating the Calculated Off-block Time (COBT), managing queuing aircraft at holding points, and identifying potential conflict points

in the taxiing process. Taxiing time prediction has been the focus of research involving various modelling techniques, such as queuing models (Pujet et al., 1998; Idris et al., 2001), fuzzy rule-based systems (Chen et al., 2011), statistical approaches (Lordan et al., 2016), and machine learning techniques (Balakrishna et al., 2010). Meanwhile, identification of key state variables and relevant factors as well as their relative importance each play a role in high-quality prediction (Wang et al., 2021).

2) Taxiing Speed control

Taxiing speed is not only directly related to the total taxiing time on the airport surface, but also relates to fuel burn and emission profiles. Therefore, it is concerned with KPAs such as efficiency and environmental impacts (ICAO, 2005a).

Recently, studies have been focusing on taxiing speed control, which attempts to develop high-resolution speed profiles with the expected benefits of fuel saving and emission reduction on the taxiway. This line of studies investigates the potential trade-off between total taxiing time and fuel consumption (Chen et al., 2011; Ravizza et al., 2013b). This is driven by the observation that a taxiing aircraft needs to maintain a high average speed through a number of deceleration and acceleration cycles to achieve minimum taxiing time. However, acceleration, idling, constant-speed taxiing and braking are significant factors affecting fuel burn and emissions (Khadilkar and Balakrishnan, 2012; Nikoleris et al., 2011). Therein lies the complexity in formulating optimal speed control while taking taxiing time and environmental factors into considerations.

Existing studies of speed profiles are subject to a fixed taxi time experienced on a given taxiway segment. To simplify the calculation, the speed profile on the taxiway segment is further divided into three or four phases, namely acceleration, travelling at a constant speed (Zhang et al., 2018), braking and rapid braking (Weiszer et al., 2015b; Chen et al., 2015a&2015b&2016). However, limitations exist in these approaches. Firstly, the complexity increases dramatically when dealing with a fleet of aircraft taxiing aircraft simultaneously, given the lack of explicit consideration of conflicts. Secondly, the speeds at the control points are fixed, subjected to a

speed range that is determined by the taxiway type, which is not in line with the real-world operational environment. Thirdly, the four phases combined do not fully represent sophisticated taxiing manoeuvres and are likely to be sub-optimal when it comes to taxing time, fuel consumption, and emissions (Khadilkar and Balakrishnan, 2012). On the issue of real-world implementation, moving on the airport surface is frequently influenced by manual operations and instructions. Thus, one needs to consider uncertainties associated with deviations from the designed speed profiles and propose conformance alerts as well as speed recovery solutions.

3) Sequencing optimisation

Some literature has focused on the sequencing at critical points (e.g. intersections, nodes, edges) to improve the ground operation efficiency. Smeltink et al. (2004) and Rathinam et al. (2008) considered estimated off-block time, estimated take-off time, and some other safety constraints (e.g. jet blast), in determining the sequence of flights passing through certain nodes or edges along a fixed route. This has led to reduced conflicts and improved operational efficiency, but to a limited degree because the routes are fixed, leaving little room for effective conflict resolution. Besides sequencing at intersections of the taxi network, the departure sequencing at the runway threshold has also been considered within the framework of taxiing planning to ensure that the aircraft arrives at the runway for take-off at an appropriate time interval, rather than merely reducing the total taxiing time (Gotteland et al., 2001; Rathinam et al., 2008; Deau et al., 2008).

4) Taxiing scheduling and routing

The majority of literature along this line of research focused on optimising the taxiing route (i.e. route assignment) for each flight considering the dynamic traffic flow on the surface. Marin (2006) and Marin and Codina (2008) proposed space-time network models based on mixed integer linear programs (MILPs), which allow taxiing routing and scheduling to be simultaneously optimised. However, MILP-based approaches typically suffer from the curse of dimensionality, which renders efficient calculation of optimal solutions infeasible for large-

scale networks or real-time applications. This is especially true when the airport suffers from unexpected events which result in urgent re-planning (Clare and Richards, 2011; Marin, 2013). In light of this drawback, a set of available routes for each flight was predefined in Balakrishnan and Jung (2007) and Roling and Visser (2008) to reduce the search space and hence improve computational tractability. Some other work on integrated optimisation of taxiing scheduling and routing using predefined sets of routes can be found in (Pesic et al., 2001; Gotteland et al., 2003; Herrero et al., 2005; García et al., 2005).

3.2.5. Integrated Airport Surface Management

The literature reviewed above has studied the operation of individual component (e.g. runway, taxiway, apron) on the airport surface, which is in contrast to more integrated ground movement management that involves several components simultaneously, which holds promise to effectively reduce congestion and improve efficiency. This subsection summarises the research of integrated airport surface operation.

3.2.5.1 Integration of runway and taxiway operations

Ground movement has a direct relationship with departure sequence. As pointed out in Atkin (2010) and Section 2.3.2 of this thesis, the taxiing process is closely interconnected with runway scheduling and sequencing. An individual component (runway, taxiway, apron) does not work properly without consideration of the interface with the others. For example, an optimal departure sequence is only effective if the particular aircraft reach the runway at their allocated departure time slots, which is non-trivial given the highly complex taxiing process with its many uncertainties and individual interactions. Much of previous work therefore focused on the integrated optimisation of the taxiing process and runway operation for the purpose of delivering an optimal runway sequence through taxi routing or scheduling.

A set partitioning model proposed by Yu and Lau (2014) is among the first to consider such integration, which largely reducing the number of constraints and making the problem more

manageable. In their modelling, each feasible taxiing route was regarded as a decision variable and two more constraints were proposed to enforce a minimum separation distance between aircraft on the taxiway and runway. This model has been tested on a small taxiway network of 36 nodes with one runway, and the computational time was not reported. Due to distinct characteristics on the taxiway and the runway, much of previous research, for the sake of convenience in solution methods, decomposed such complex problem into two sub-problems sequentially. In general, the first stage is concerned with the runway sequence/schedule optimisation. Based on the determined optimal runway sequence/schedule (as constraints), available taxiing routes or taxiing schedule are worked out in the second stage. Deau et al. (2008&2009) considered a sequential approach where a departure sequence was optimised in the first stage, which provided an optimal take-off slot for aircraft, and this was used to work out a feasible taxiing route along with gate release time in the second stage. The conclusion drawn was that only one half of the total delays on the surface were attributed to the runway bottleneck, thus highlighting the importance of coordinating taxiway and runway operations simultaneously. Benlic et al. (2016) presented the first local search heuristic algorithm, based on Iterated Local Search to solve the coupled runway sequencing and taxi routing problem, with the objective of minimising total taxi and completion times. Their research found that a significant reduction in taxiway routing delays can be achieved without compromising runway performance, in contrast to sequential optimisation approaches. Other research of integrated runway and taxiway operations can be seen in Guepet et al. (2017), Atkin et al. (2013), Bertsimas and Frankovich (2013), Pavese et al. (2017).

3.2.5.2 Integration of runway sequences and TMA operation

The integrated optimisation of taxiway movement and runway scheduling has been extended in some research to include the Terminal Manoeuvring Area (TMA). This is done by considering departure and arrival procedure constraints to jointly optimise the airport surface and airspace terminal activities. Bosson (2015) studied the optimisation of integrated airport

surface and terminal airspace operations. In this research, the departure and arrival sequences were jointly optimised based on gate assignment, and a set of predetermined taxiing routes on the surface as well as departure and arrival routes in the terminal airspace in accordance to STARs and SIDs. The objective was to minimise the combined total taxiing time on the surface and flying time within the terminal airspace, by determining the arrival sequence for arrivals and pushback time for departures subject to estimated pushback time, speed range and wake vortex. The highlight in this research is that uncertainty was considered by generating stochastic scheduling for arrivals, and the proposed optimisation method was tested in various scenarios. Ma et.al (2016&2018) also considered both TMA and airport in a two-level optimisation framework. The first stage stipulates the runway assignment (departure and arrival) and landing time through proper adjustment of timing decisions, considering a series of constraints in TMA (i.e. arrival fixes, departure fixes) at the macroscopic level. In this stage, the airside was modelled as an abstract network, and each component (runway, taxiway, and terminal) was allocated a maximum capacity. In the second stage, a meta-heuristic model combined with a time decomposition approach was proposed to calculate the pushback time and taxi route at the microscopic level. The result showed that the pushback delay and waiting time at runway threshold were significantly reduced.

The results of previous studies confirmed the benefits of optimising several key components in an integrated manner. However, the literature reviewed above achieved only partial integration. In particularly, in these studies the taxi routing problem in the second stage is highly dependent on the result of the runway sequence obtained in the first stage (Atkin, et al., 2009; Atkin, et al., 2012; Guepet et al., 2017; Benlic et al., 2016), no consideration is given to how runway sequencing could be jointly determined with taxi planning. Moreover, apron congestion, due to gate holding that arises from pushback controls, results in the shortage of gates and increased taxi time within the apron, which is not considered in the research (Benlic, et al., 2016; Guepet et al., 2016). Furthermore, these studies are typically confined to a fixed network topology with given origin-destination (runway and apron) pairs for departures and arrivals (Atkin, et al., 2009; Atkin, et al., 2012; Guepet et al., 2017; Benlic et al., 2016). No studies have fully

explored the joint runway-apron assignment on the airport surface, as well as subsequent taxiing routing and pushback controls that would benefit from a new O-D configuration.

3.2.5.3 Other integrated operation

The majority of studies on gate assignment aim to minimise the walking distance of different kinds of passengers in terminals (Maharjan et al., 2011), or minimise congestions and delays within aprons (Zhang and Klabjan, 2017; Dorndorf et al., 2012&2017). Notably, the assigned gates/stands for aircraft have a direct impact on the operations of taxiway and runway, instead of merely considering terminals or aprons. Having realized this, Kim et al. (2011&2013) presented metaheuristic algorithms to solve a gate assignment problem while simultaneously minimising the taxi-in time of aircraft on the airport surface and the walking distance of passengers in the terminal. However, this work largely simplifies the taxiway network configuration and dynamics by approximating the taxi-in time as a distance covered at an average speed, instead of considering detailed taxiing dynamics and interactions among aircraft on the surface.

Integrated aircraft and shuttle bus operations on the airport surface was considered in Weiszer et al. (2015a). They adopted a systematic approach to integrated taxiway routing and scheduling, runway scheduling and airport bus scheduling. This is done with fixed apron and runway assignment information. Their work also ignores the interactions among aircraft taxiing on the surface network at the same time.

3.3. Selected case study: Beijing Capital International Airport

To assess the validity and effectiveness of the proposed concept and methodological framework, a case study of Beijing Capital International Airport (PEK) is considered. The PEK is 1) among the busiest airports in terms of passing throughput in the world, 2) currently operating at a nearly saturated level, and 3) characterised by a highly complex surface network in terms of both physical configuration and allocation of various airport resources. The details of the case study are presented below.

3.3.1. Brief Introduction of PEK Operation

PEK is the second busiest airport in terms of passing throughput in the world from 2010 to 2019, only followed by Atlanta-Hartsfield-Jackson Airport which continues leading the ranking. Figure 3.4 shows annual flight movements and passenger throughput over the period from 2010 to 2019. During the ten years, there is a steady increase in passenger throughput from 73.9 million in 2010 to over 100 million in 2019, where the passenger throughput has exceeded 100 million in 2018 for the first time after 5.4% interannual growth. On the other hand, the annual flight movements have a gradual increase; that is, from 0.53 million in 2011 to 0.61 million in 2018, and with a slight fluctuation in 2010 and 2019.

In addition, PEK is now operating at high demands with around 1700 flights per day from 94 airlines, linking Beijing to approx. 250 domestic and international cities in China and in the world. The claimed capacity of PEK is 88 per hour, which means that under certain circumstance (e.g. appropriate ratios of arrivals and departures, proper weather condition, no construction work), the sum of arrivals and departures operating on three runways in peak hour can reach up to 88 per hour. In reality, PEK was already operating close or even over its claimed capacity in most of the peak hours. Figure 3.5 shows one typical day of operation at PEK, with a total of 1757 flights. As shown in this figure, from 6:00 am to 23:00, the airport was operating at a volume close or even over the claimed capacity. In particular, from 06:00 to 09:00, there was a high departure demand, whereas from 21:00 to 24:00 a heavy demand for arrivals was shown.

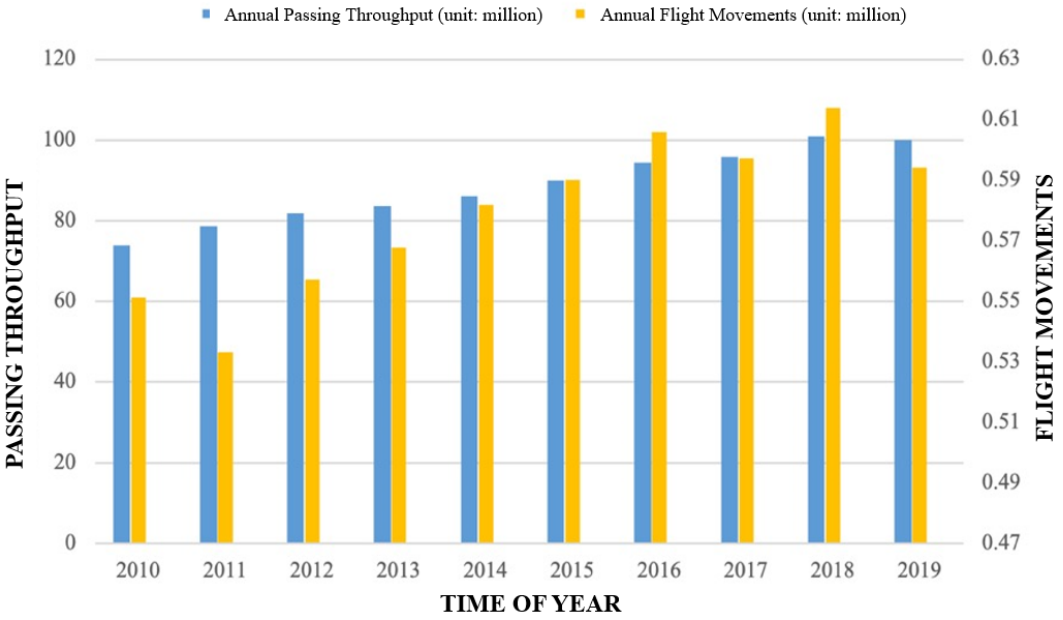

Figure 3.4. Operation volume of PEK from 2010 to 2019

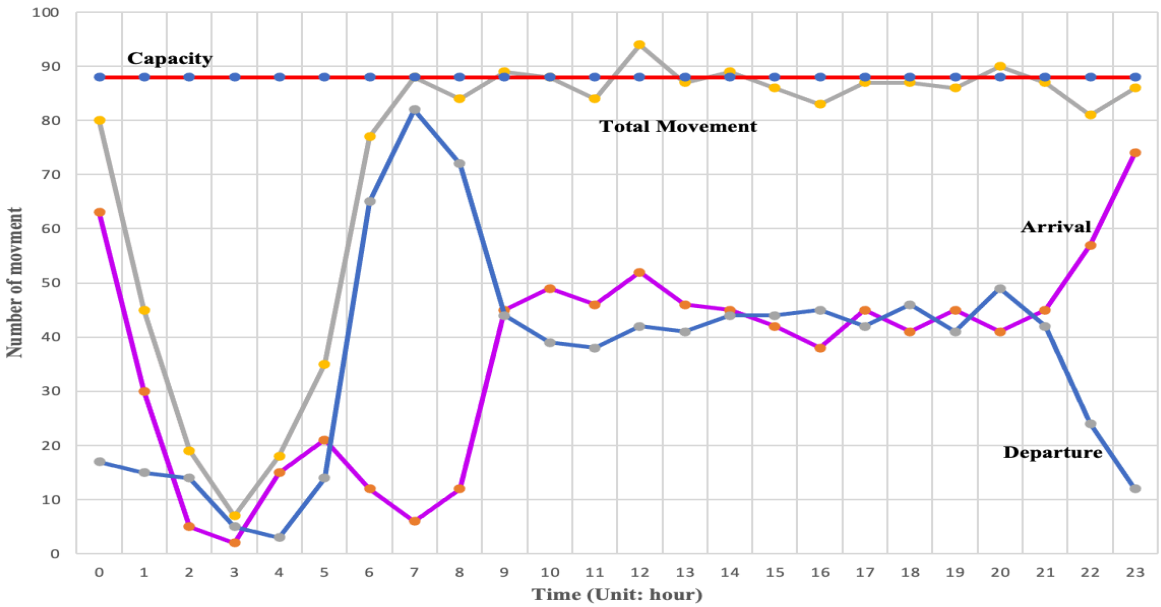

Figure 3.5. Hourly movements at PEK on 14/09/2017

3.3.2. PEK Surface Topology

PEK is a 4F level airport[13], consisting of three parallel runways (01/19, 36R/18L and 36L/18R), with three terminals (T1, T2 and T3) and 314 stands (including bridge stands and remote stands). In general, the airport surface is comprised of two areas, named East area and West area. The area located in the east of the middle runway (i.e. the area between RWY 01/19 and RWY 36R/18L) is referred to as the East Area, while the area located in the west of the middle runway (i.e. the area between RWY 36L/18R and RWY 36R/18L) is referred to as the West Area. Terminal 1 and Terminal 2 are located in the West Area, while Terminal 3 with three independent buildings, named Building C, Building D and Building E, are located in the East Area. The trains are operating within three buildings of Terminal 3 for transferring passengers, whares shuttle buses are used within different terminals. An aerial view of the PEK Airport is shown in Figure 3.6.

The three runways are parallel. The space between them (from the West Runway to the East Runway) are 1960m and 1525m, respectively. The basic runway information is summarised in Table 3.2. Such a large space between each runway meets the requirement (no less than 1035m) of the independent operation, both for arrival and departure. Figure 3.7 shows a schematic diagram of the mixed operation in the north direction, which is the prevailing direction of the runway operation at PEK Airport (up to 82% per year according to one-year data statistics and ATC survey), with runways being designated 01, 36R and 36L, respectively.

[13] The airport airside is classified into six levels from small to large A, B, C, D, E, F, according to the allowable maximum wingspan and the main landing gear. A 4F level airport should have comprehensive facilities and infrastructures to fully support all activities in terms of take-off and landing for Airbus A380.

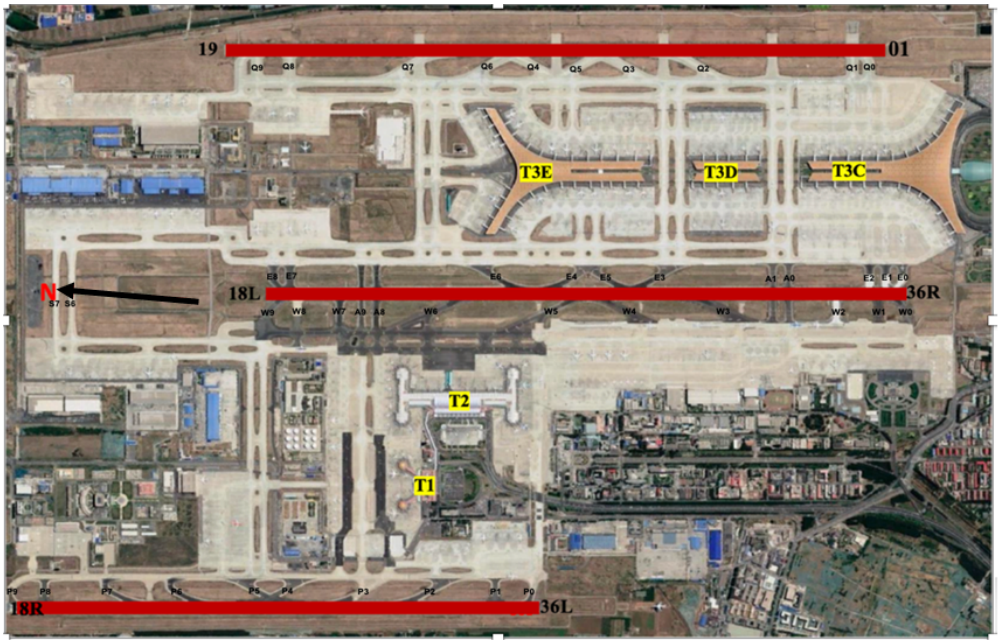

Figure 3.6. Aerial view of PEK airport (adopted from Google Map)

Table 3.2. Basic information of runways at PEK airport

Area	Number	Angle	Length	Width	Operation Mode
East	01(North)	359	3799m	60m	Arrival/Departure
	19(South)	179	3799m	60m	Arrival/Departure
Middle	36R(North)	359	3799m	60m	Arrival/Departure
	18L(South)	179	3799m	60m	Arrival/Departure
West	36L(North)	359	3200m	49m	Arrival/Departure
	18R(South)	179	3200m	49m	Arrival/Departure

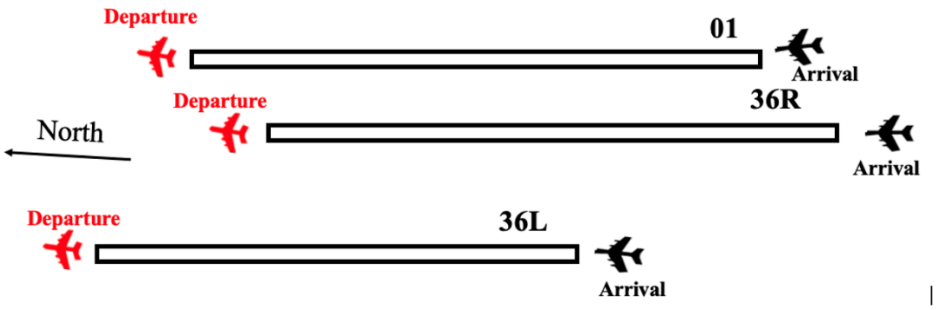

Figure 3.7. Schematic diagram of three runways at PEK

All airlines operating at PEK are accommodated in the three terminals, where a series of pre-flight and after-flight activities for passengers should be done, such as check-in, flight information inquiry, security check, departure lounge, and luggage claim. Until to May 2020, six base airlines are operating in PEK. They are Air China (IATA: CA), China Eastern Airlines (IATA: MU), China Southern Airlines (IATA: CZ), Hainan Airlines (IATA: HU), Capital Airlines (IATA: JD), and SF Airlines (cargo airline). Besides, a total of 94 airlines are distributed in three terminals (T1, T2 and T3) according to airline attributes (e.g. base or non-base, flight alliance) and flight attributes (i.e. international or domestic). T1 is accommodating Hainan Airline group (HNA), T2 is operating all SKY TEAM airlines, including both base airlines (MU, CZ, HU international) and non-base airlines, as well as part of non-alliance foreign airlines. Both of Star Alliance-belonged (e.g. CA, LH) and Oneworld-belonged airlines as well as remaining non-alliance foreign airlines are operating in T3. Table 3.2[14] shows basic information of each terminal, as well as airlines' distribution at PEK.

[14] The information in Table 3.3 was cited in 2017, which is consistence with the historical data used.

Table 3.3. Airline distribution at PEK airport (adopted from BCIA (2017)

Terminal Number	Terminal square (m^2)	Number of stands	Airlines Code (IATA)[15]
Terminal 1	60,000	164	FU; CN; JD; GS; 9C; 8L
Terminal 2	3,360,000		AL; JD (I); N4; ZA; NN; 7J; PS; 7C; NS; 2D; J2; Y7; R3; D7; HZ; 5J; FM; DL; CZ; OQ; HU; MU; MF; KE; AF; SU; HY; KL; KC; JS; PK; GA; IR; UL; T5; VN; DT; AH; HX; LV
Terminal 3	9,860,000	150	AZ; DZ; HM; KY; W5; GJ; QW; HA: TV; GH; MK; LO; CA; LX; CA; SC; 3U; OS; SK; LH; OZ; AC; UA; NH; TK; MS; TG; SQ; AY; CX; BA; JL; KA; EK; LY; QR; S7; NX; CI; EY; BR; ZH; OM; U6; AA; UN; ET; PR; MH; HO

Furthermore, this proposed research is performed by considering runway and apron assignment rules, constraints, and preference, taxiway and TAM rules and constraints. These rules, constraints, and preferences adopted in PEK, although differ in detail, are broadly similar in all Chinese airports.

In light of the above, given the provision of data and extensive collaboration of the PEK for the validation of the developed concept, PEK is a typical airport applied to this proposed research, and thus serves as a case study in this thesis. The proposed IARA-IDRO framework described in this thesis is applied to PEK using a combination of qualitative assessment (i.e. interviews and questionnaire) and quantitative assessment (i.e. mathematical and simulation models in Chapters 5 & 6 & 7 & 8. The details are described in the relevant chapters.

[15] IARA codes refer to Appendix 4.

3.4. SUMMARY

This chapter has reviewed operational concepts and initiatives, emerging technologies and procedures proposed by SESAR and NextGen (see Section 3.1) and academic studies, all of which are intended to enhance and improve airport operations (see Section 3.2) and the selection of a case study for the purpose of validation (see Section 3.3). The current literature has focused on the optimisation of runway, taxiway and apron operations, whether individually or partially integrated. To date, the investigation of joint optimisation of all three components has not been found in the literature due to its complexity in terms of operational constraints, assignment rules, and the number of stakeholders (Atkin, 2010). Despite that, all these three components are interconnected and interdependent from both the physical connections and the operational perspectives (see Sections 2.2.2 & 2.3.2). This lack of integration results in sub-optimality and inefficiency, i.e., excessive runway queuing, aircraft conflicts, and passenger delays.

In addition, another critical aspect of current existing studies on gate assignment is that they are driven by either passenger-related objective within terminals, or optimisation of operations within aprons with a limited view of network-wide surface movements. The is no current research on gate/apron assignment from the perspective of network optimisation, due to the high level of complexity of large-scale network flows. The limited integration of gate assignment and surface movement not only adds uncertainties to the gate/apron assignment problem, but also overlooks its broader impact on airport operation (e.g., taxiing distance, taxiing time, and conflicts) as a whole.

To address the above research gap, multi-scale and multi-stage modelling, as well as optimisation frameworks, are proposed using both quantitative and qualitative methods. This is directly related to: (i) the proposed integrated runway and apron assignment (IARA) model from the perspectives of network optimisation on a pre-tactical level (see Chapter 5), (ii) taxiway routing (for both arrivals and departures) (DRS) model and (iii) integrated dynamic routing and off-block control (for departures) (IDRO) model on a real-time operational level

(see Chapter 7). To assess the validity and effectiveness of the proposed framework, a quantitative validation in terms of comparisons of KPIs was conducted, based on a case study of PEK (see Section 6.3) and simulation outputs of each proposed model (see Sections 8.4 & 8.5 & 8.6). All numerical results were confirmed by SMEs, and potential applications as well as implementation suggestions have been provided by the SMEs and various stakeholders (see Section 8.1.3)

Before modelling the design, Chapter 4 reviews several network modelling techniques that have been used to analyse aircraft traffic flow characteristics and model the aircraft movements on the airport surface.

CHAPTER 4 AIRPORT SURFACE TRAFFIC NETWORK MODELLING

This chapter studies traffic flow characteristics in terms of apron taxiway and runway dynamic characteristics (see Section 4.1). Based on these dynamic characteristics, typical traffic network models: Cell Transmission Model for Airport surface (A-CTM) (see Section 4.2) and Cellular Automata for Airport surface (A-CA) (see Section 4.3) are respectively proposed, following by a summary in Section 4.4.

4.1. TRAFFIC FLOW CHARACTERISTICS AND DYNAMICS

Prior to modelling the airport surface movement, dynamic characteristics of aircraft on the airport surface should be derived. Although road traffic and aircraft movement have some similarities, aircraft movement differs from the vehicles in many parts due to their unique dynamics as well as various operational rules and constraints.

An airport surface network consists of directed links and junctions. Figure 4.1 shows an example of the surface network consisting of runway, taxiway, and apron networks. These sub-networks have diverse configurations and flow characteristics. In particular, the taxiway network connects the runways with the apron network, and is where most merging, diverging, and crossover behaviour takes place. It is also the main location that generates congestion and delay.

Similar to road traffic, the aircraft movement at airport surface is characterised by the balance between demand and supply, which are typically captured by a density-flow relationship known as the fundamental diagram (Daganzo, 1994). In order to empirically study the flow characteristics of airport surface, the historical flight data collected form Guangzhou Baiyun airport on July 22 2014, is adopted, which are distinguished by apron and taxiway.

Figure 4.2 shows the density- speed- flow relationships that exist on a link level. The FDs in Figure 4.2 were established for all the links of apron and taxiway sub-networks. This is justified

by the general taxiing regulations, which imply that air traffic (both taxi-in and taxi-out) along each link in the same sub-network are homogeneous. Moreover, the density values are derived from all the aircraft travelling along the links, including both taxi-in and taxi-out.

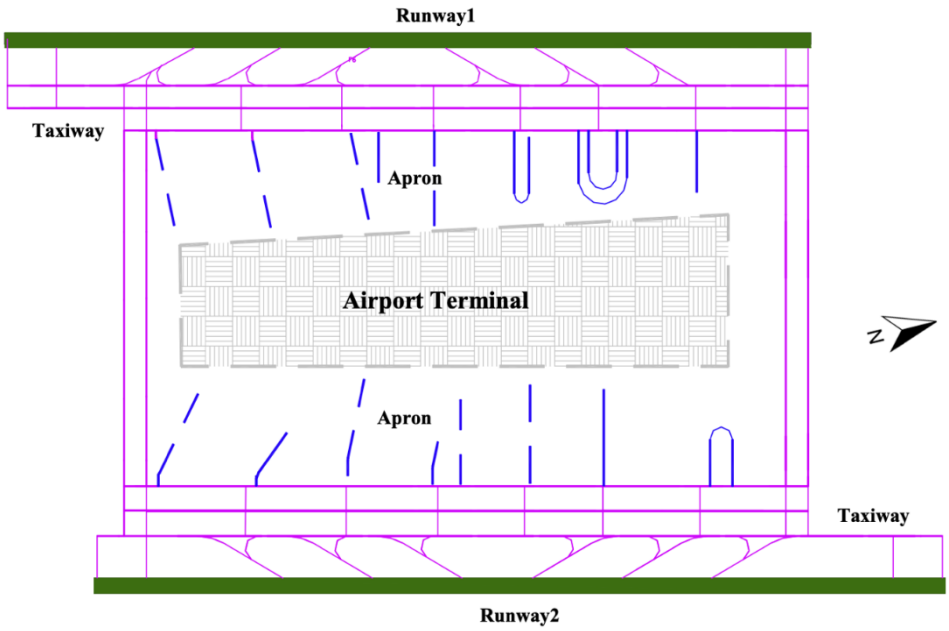

Figure 4.1. Schematic diagram of airport surface network (Yang et al., 2017)

Figure 4.2 shows two distinct phases for both apron and taxiway movements; that is, a free-flow phase and a congested phase. Overall, the relationships are consistent with the fundamental diagrams in road traffic, yet with the following distinctive features.

- In the free-flow phase, due to different taxiing speed restrictions of different airlines and/or aircraft types, the variation in speed is relatively high in the low-density region compared to road traffic. This is apparent from the density-speed diagram.
- There exist qualitative differences between the fundamental diagrams of the apron and taxiway. Firstly, the congested region of taxiway traffic is much more scattered because the speed is much higher in taxiways and prone to high variations. Another reason for

the low variation in the congested phase of apron traffic is the gate assignment strategies applied by the airport operation centre, which proactively avoids potential conflicts in the apron area.

- Extremely high density is hardly observed in the apron area. The reason is that the controllers tend to hold aircraft at the gates when a foreseeable conflict comes up. In contrast, severe queuing is much more common on taxiways especially at the runway queuing area.
-

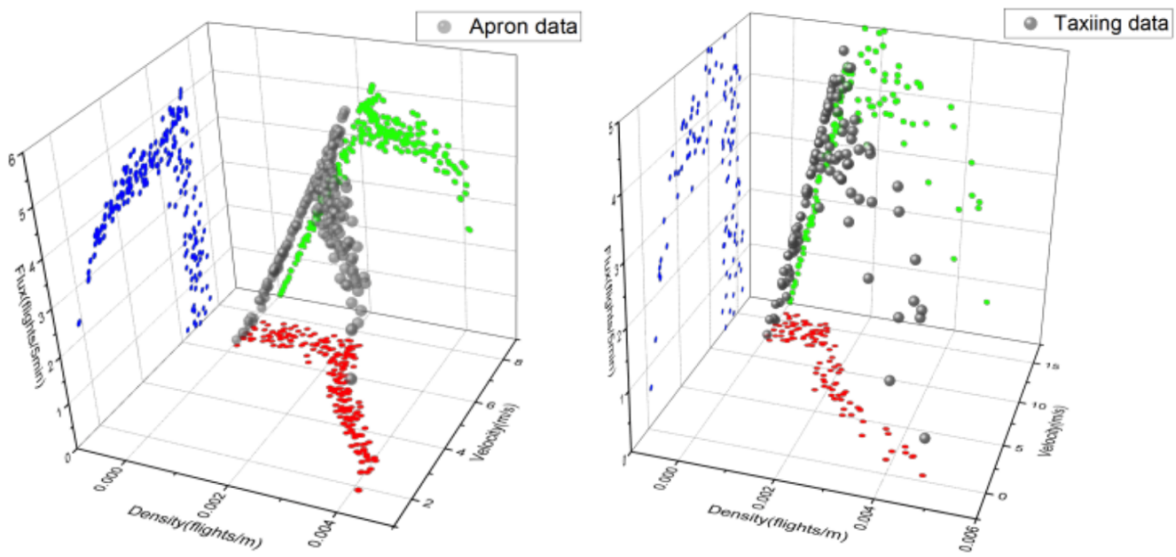

Figure 4.2. Empirical flow-density-speed relationship of traffic flow at apron area and taxiway (Yang et al., 2017)

4.2. CELL TRANSMISSION MODEL FOR AIRPORT SURFACE TRAFFIC

4.2.1. Introduction

Cell Transmission Model (CTM) is a popular macroscopic traffic model, which is based on Godunov discretization of the well-known Lighthill-Whitham-Richards (LWR) kinematic wave model of car traffic (Lighthill and Whitham, 1955; Daganzo,1994&1995), consisting of a number of homogeneous cells with proper size, along with a time discretization scheme flowing the Courant-Friedrichs-Lewy (CFL) condition (Courant et al., 1928). The CTM model is capable of simulating traffic's evolution over time and space, where current conditions are updated with every tick of a clock, including congestion building, propagation, and dissipation, which is widely adopted in large and complex road network (Alecsandru, 2006).

Given the similarities between the airport surface traffic and road car traffic, this subsection introduces an adaptation of the CTM to describe the dynamics of traffic flow on airport surface network.

4.2.2. Fundamental Diagram on Airport surface

As suggested by the empirical data (Figure 4.2), the Fundamental Diagram (FD) for the movement of aircraft on the airport surface is conducted. The FD describes the relationship between aircraft density and flow along a homogeneous segment. The CTM is based on a trapezoidal or triangular fundamental diagram (Figure 4.3), and propagates flow and congestion through straightforward bookkeeping, which is able to capture, in an effective way, traffic flow characteristics and mechanisms under which congestion forms, propagates, and dissipates, within an efficient computation for large and complex road or airport surface networks.

The cell size is set as Δx and time increment is Δt, such that the CFL condition $\Delta x/\Delta t \geq v$ holds, where v denotes the free-flow speed. The following notations are used in this chapter.

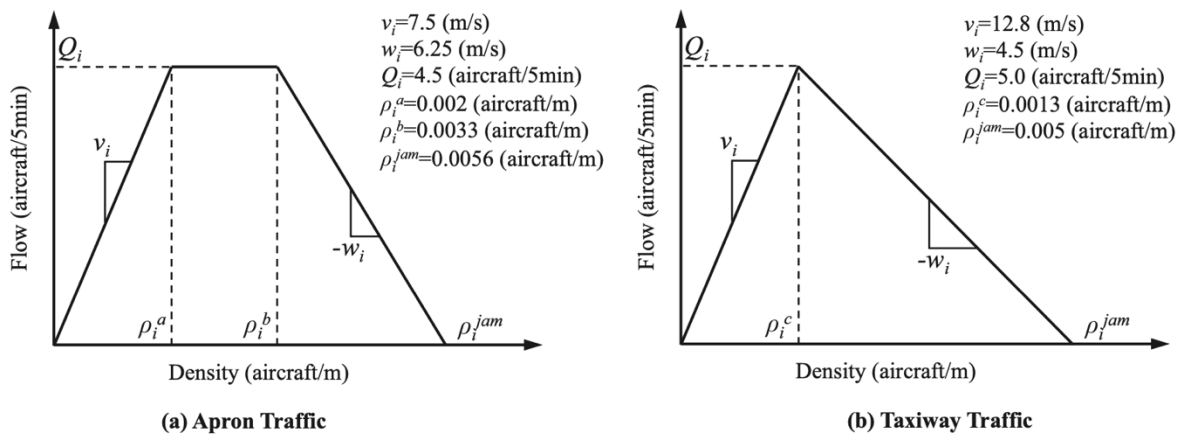

Figure 4.3. Density-flow relationship of traffic flow at apron or taxiway links. Left: Trapezoidal (apron traffic); right: Triangular (taxiway traffic).

v_i:	Forward wave speed (free-flow speed) of cell i; see Figure 4.3
w_i:	Backward wave speed
Q_i:	Maximum number of aircraft that can be transmitted through cell i within one time step
$m_i(t)$:	The number of aircraft in cell i during time step t
$y_i(t)$:	The number of aircraft entering cell i from its upstream cell $i-1$ during time step t
M_i:	The holding capacity of cell i (i.e. the product of the cell length and jam density)

Unlike car traffic, a minimum spatial headway between two taxiing aircraft must be strictly maintained according to International Civil Aviation Organization (ICAO) regulation (not less than 50m) due to aircraft jet blast. It is vital to investigate the specific separation standard when modelling individual aircraft. The spatial headway matrix adopted in the Guangzhou Baiyun international airport (IATA: CAN), is shown in Table 4.1 (Yang et al., 2017).

Let p_{ab} be the probability that the leading aircraft is of type a and the trailing aircraft is of type b; let D_{ab} be the minimum separation as shown in Table 4.1 $(a, b \in \{L, M, H\})$. The probability p_{ab} can be estimated using field data. Then, the average minimum separation $\overline{D}$ can be estimated as $\overline{D} = \sum_{a,b} p_{ab} D_{ab}$. Therefore, the maximum number of aircraft a cell of size Δx can hold can be approximated as

$$\boldsymbol{M_i} = \frac{\Delta \mathbf{x}}{\overline{\mathbf{L}} + \overline{\mathbf{D}}} \tag{4.1}$$

Where $\overline{L}$ denotes the average aircraft length.

4.2.3. Details of A-CTM

It is important to note that the surface network links are uni-directional for all the taxi-in and taxi-out aircraft for the following reasons. To avoid head-on conflict and to reduce the workload of ground controllers, all the taxiing routes, which link the runway and the gates, are pre-determined and traverse uni-directional links. This means, once the runway direction and mode are determined, only one travelling direction is permitted for each link, for both taxi-in and taxi-out aircraft.

Each link in the network is partitioned into a number of cells of appropriate size, along with a time discretization scheme following the Courant-Friedrichs-Lewy (CFL) condition (Courant et al., 1928). The fundamental diagrams corresponding to different types of sub-networks are used to derive cell and transmission parameters. In Section 4.2.3.1, the flow propagation through ordinary, merge, diverge, and crossover cells are described by integrating the modelling procedure from Daganzo (1994) and Daganzo (1995) with the unique characteristics of surface traffic. In Section 4.2.3.2, some unique modelling scenarios specific to airport surface are discussed and novel techniques are introduced to capture their essential operational features.

4.2.3.1. Ordinary cell

The fundamental recursion for the dynamics in ordinary cells is given as (Daganzo, 1994, 1995).

$$\begin{cases} \boldsymbol{m_i(t+1) = m_i(t) + y_i(t) - y_{i+1}(t)} \\ \boldsymbol{y_i(t) = min\left\{(t), Q_i, \frac{w_i}{v_i}(M_i - m_i(t))\right\}} \end{cases} \tag{4.2}$$

In addition, the demand and supply of a cell is defined as:

$$\begin{cases} \boldsymbol{D_i(t) = \min\{Q_i, m_i(t)\}} \\ \boldsymbol{S_i(t) = \min\left\{Q_i, \frac{w_i}{v_i}(M_i - m_i(t))\right\}} \end{cases} \tag{4.3}$$

The demand $D_i(t)$ represents the maximum number of aircraft that can be sent from cell i during time step t, and the supply $S_i(t)$ represents the maximum number of aircraft that can be received by cell i during time step t.

Table 4.1. Spatial headway matrix

Type of leading aircraft	Type of trailing aircraft		
	Light (L)	Medium	Heavy (H/SH)
Light (L)	100	100	100
Medium (M)	200	200	200
Heavy (H/SH)	300	300	300

Before discussing the junction models, an important distinction between car traffic and airport surface traffic is the existence of a point-capacity constraint (indicated as M in Figure 4.4) at the junctions (merge/diverge/crossover) of the airport surface. This is mainly due to wingspan collision avoidance as illustrated in Table 4.1. In practice, a circular protection zone of radius

R poses the separation constraints in addition to the vortex-induced minimum separation $\overline{D}$. However, given the current aircraft sizes, such a circular zone is usually no bigger than 50m in radius, which is much smaller than the vortex-induced separation (see Table 4.1). Thus, when both constraints apply, the latter always prevail. In addition, the vortex-induced separation constraint only applies when the leading and trailing aircraft are travelling in the same direction. These facts are crucial for the discussion of the junction models below.

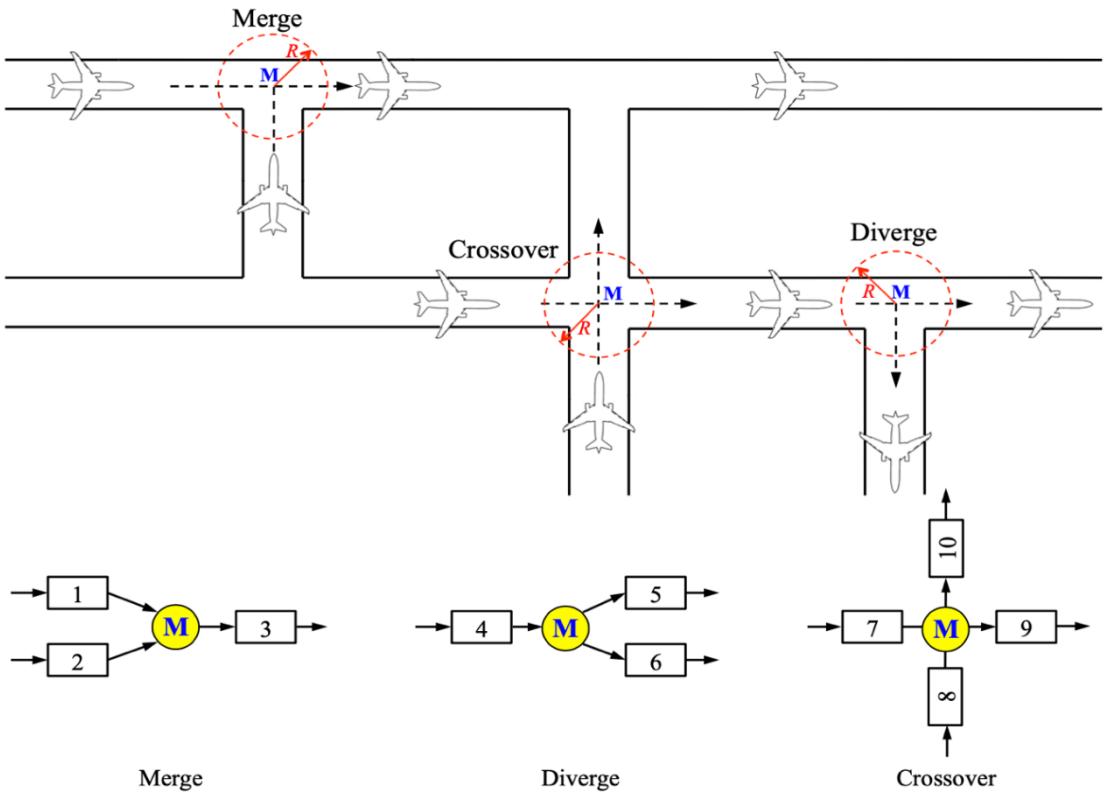

Figure 4.4. Merge, diverge, and crossover junctions. No turning is allowed at the crossover junction

4.2.3.2. Merge cell

The merge junction shown in Figure 4.4, is first considered. As can be seen from Figure 4.4, any two aircraft exiting from the upstream cells will face the same direction of travel (i.e. in

the downstream cell), therefore the vortex-induced separation constraint applies here, while the wingspan constraint can be ignored.

Let $y_{1\to3}(t)$ be the number of aircraft transmitted from cell 1 to cell 3 during time step t; similar notations are used below with obvious meanings. The following demand and supply constraints must be satisfied:

$$\boldsymbol{y_{1\to3}(t) \le D_1(t), y_{2\to3}(t) \le D_2(t), y_{1\to3}(t) + y_{2\to3}(t) \le S_3(t)} \tag{4.4}$$

In addition, flow coming from cells 1 and 2 receive certain priorities is assumed, $p_1 > 0$ and $p_2 > 0$ such that $p_1 + p_2 = 1$. The air traffic controller should ensure the equity of aircraft operations besides safety and efficiency. In merge scenarios, the upstream taxiway segment with more aircraft is normally assigned higher priority to avoid the accumulation of congestion on that segment. The demand-based priority rule (Jin and Zhang, 2003) is selected to best interpret such an equity principle. This rule stipulates that the discharge flows $y_{1\to3}(t)$ and $y_{2\to3}(t)$ follow the same ratio as the demand-based priorities $p_1(t)$and $p_2(t)$. The solution is given explicitly as:

$$\begin{cases} \boldsymbol{y_{1\to3}(t) = min\{D_1(t), p_1(t) \cdot min\{S_3(t), D_1(t) + D_2(t)\}\},\ \ p_1(t) = \dfrac{D_1(t)}{D_1(t) + D_2(t)}} \\ \boldsymbol{y_{2\to3}(t) = min\{D_1(t), p_2(t) \cdot min\{S_3(t), D_1(t) + D_2(t)\}\},\ \ p_2(t) = \dfrac{D_2(t)}{D_1(t) + D_2(t)}} \end{cases} \tag{4.5}$$

4.2.3.3. Diverge cell

The diverge junction is shown in Figure 4.4. Since aircraft discharged from the upstream cell travel in the same direction before turning to the downstream cell, only the vortex-induced separation constraint applies.

It is assumed that flow leaving cell 4 advances to cells 5 and 6 according to some turning ratios $\alpha_{4\to5}(t) \geq 0$ and $\alpha_{4\to6}(t) \geq 0$, which sum up to be one. In view of (4.4) and the flow maximisation principle, it is easy to derive the following solution for the diverge junction:

$$\begin{aligned} \boldsymbol{y_{4\to5}(t) = \alpha_{4\to5}(t) \cdot min\left\{D_4(t), \frac{S_5(t)}{\alpha_{4\to5}(t)}, \frac{S_6(t)}{\alpha_{4\to6}(t)}\right\}} \\ \boldsymbol{y_{4\to6}(t) = \alpha_{4\to6}(t) \cdot min\left\{D_4(t), \frac{S_5(t)}{\alpha_{4\to5}(t)}, \frac{S_6(t)}{\alpha_{4\to6}(t)}\right\}} \end{aligned} \tag{4.6}$$

Note that the turning ratios $\alpha_{4\to5}(t)$ and $\alpha_{4\to6}(t)$ are not exogenously given; rather, they are determined by the pre-defined aircraft routing information, which is the input of the simulation. In this regard, the CTM-based network simulation is similar to the dynamic network loading problem extensively studied in the dynamic traffic assignment literature (Friesz et al., 2013); and further details are omitted here.

4.2.3.4. Crossover cell

Crossover junction is shown in Figure 4.4. Given that no turning is allowed at the junction, the following observation can be made:

- only the vortex-induced separation constraint is applied when two or more consecutive aircraft from the same approach advance through the junction without interruption from the other approach; and
- only the wingspan constraint is applied when the two upstream approaches take turn to discharge aircraft.

Here, the demand-based priorities p_7, p_8 are defined for the upstream cells 7 and 8, respectively, following the formula (4.5). Without loss of generality, it is assumed that $D_7 \leq D_8$, so that $p_7 \leq p_8$. Then, the probability of case (2) is $p_8 - p_7$, and the probability of case (1) is $2p_7$. Therefore, the Average Spatial Headway (ASH) is computed as:

$$\text{ASH} = (2\text{p}_7) \cdot 2R\left(\frac{meter}{aircraft}\right) + (p_8 - p_7) \cdot \overline{D}\left(\frac{meter}{aircraft}\right)$$

where R is the radius of the wingspan-induced protection zone, and $\overline{D}$ is the vortex-induced minimum separation. Assuming that aircraft move at the free-flow speed when crossing the junction, the point capacity at the crossover junction is estimated as:

$$C_M = \frac{v}{\text{ASH}} = \frac{v(D_7 + D_8)}{4D_7R + (D_8 - D_7)\overline{D}} \tag{4.7}$$

where v denotes the free-flow speed. Note that (4.7) is valid only when $\max\{D_7, D_8\} > 0$; otherwise, if both demands are zero no junction model is needed.

The flows discharged from cells 7 and 8 are constrained by not only the supplies of their respective downstream cells, but also the point capacity (4.7). The latter (CM) is shared by both incoming approaches, and a similar, demand-based priority assignment is employed as in (4.5).

$$\begin{cases} y_{7\to9}(t) = \left\{D_7(t), \dfrac{D_7(t)}{D_7(t) + D_8(t)} \cdot C_M \cdot \Delta t, S_9(t)\right\} \\ y_{8\to9}(t) = \left\{D_8(t), \dfrac{D_8(t)}{D_7(t) + D_8(t)} \cdot C_M \cdot \Delta t, S_{10}(t)\right\} \end{cases} \tag{4.8}$$

4.2.3.5. Other modelling scenarios specific of airport surface

1) Runway queuing

Departing aircraft wait at the end of the runway before taking off. Therefore, the cells towards the end of the runway are the main queuing area, whose average density will influence, not just one, but all their upstream cells simultaneously. This is due to the fact that ground control tends to meter aircraft from entering the parallel artery runway from the by-pass taxiway when the runway queuing area reaches a certain level of saturation; see Figure 4.5.

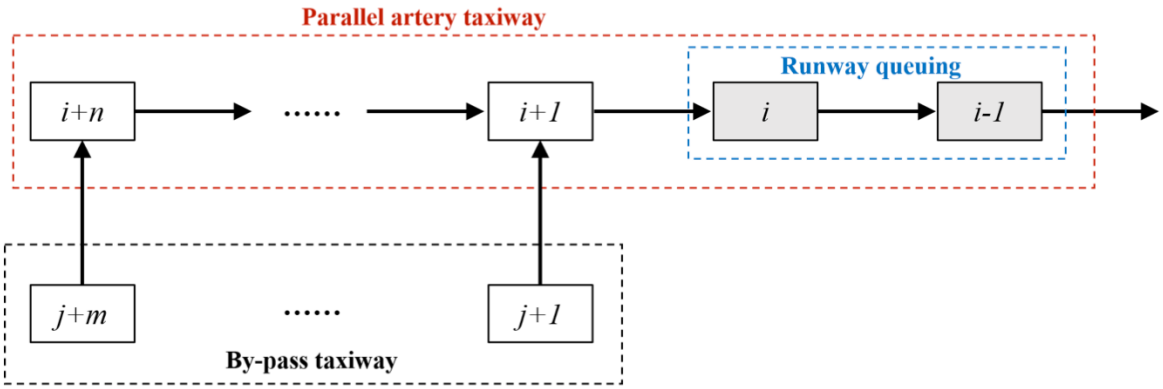

Figure 4.5. Cell representation of the runway queuing area

There are different ways to mathematically represent such a control mechanism. Here, let N^q be the holding capacity (in number of aircraft) of the queuing area at the end of the runway, and $M^q(t)$ be the total traffic volume at time t in the parallel artery taxiway. $Q_{j+z\to i+n}(t)$ denotes the transmission capacity (in number of aircraft) from cell $j+z$ to cell $i+n$ (see Figure 4.5) during time step t. When ground control is applied in view of the congestion in the queuing area, the discharge flow from the by-pass taxiway cell $j+z$ is reduced according to:

$$Q_{j+z\to i+n}(t) = \min\{Q_{i+n}, \psi_{j+z\to i+n}(t)\} \tag{4.9}$$

where Q_{i+n} is the transmission capacity of cell $i+n$, and

$$\psi_{j+z\to i+n}(t) = \max\{N^q - M^q(t), 0\} \times \gamma \tag{4.10}$$

Here, $\gamma \in (0,1)$ is some priority parameter that can be derived either exogenously according to expert experience or endogenously, e.g. proportional to the cell $j+z$'s demand, as is done. The treatment of the flow control at other by-pass taxiway cells is completely similar.

2) Runway network

In many airport surface networks, the runway serves as both the source (sink) of arriving (departing) air traffic. As shown in the left picture of Figure 4.6, the runway itself may be

modelled as a single cell (since it can be occupied by no more than one aircraft at the same time for safety reasons) located at the centre of a merge-diverge intersection.

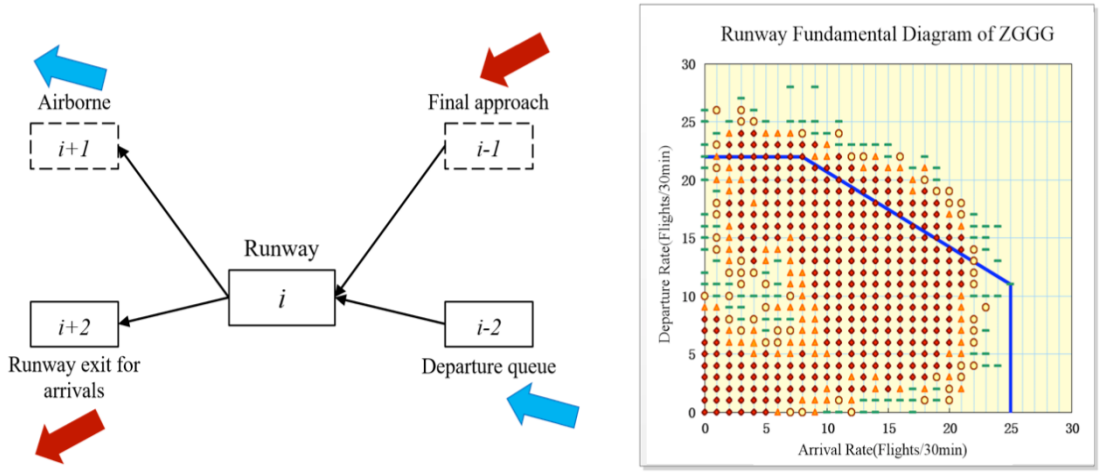

Figure 4.6. Left: the cell representation of runway network. Right: the fundamental diagram of the runway cell

In contrast to how 2×2 intersections are typically modelled for vehicular traffic (Garavello et al., 2016), the runway network has some unique characteristics. First, arrival traffic through cell $i-1$ has significant priority over departure traffic through cell $i-2$. Typically, the capacity trade-off for departure and arrival traffic is captured through the fundamental diagram of the runway, also known as the envelope model (Gilbo, 1993). An example is shown in the right picture of Figure 4.6. Due to the absolute priority of landing flow over departure flow at the final approach, the cell $i-1$ always remains in the free-flow state. Then the left-over capacity of the runway, which is given by the fundamental diagram, is assigned to departure traffic from cell $i-2$. Such a system may be expressed using the following set of equations:

$$Q_l(t) = F(y_{i-1\to i}(t)) \tag{4.11}$$

$$y_{i-2\to i}(t) = min\{m_{i-2}(t), Q_i, Q_{i-2}, Q_l\} \tag{4.12}$$

$$y_{i\to i+2}(t) = y_{i-1\to i}(t) \tag{4.13}$$

Here, $y_{i-1\to i}(t)$ denotes the arrival rate and is exogenously given, $Q_i(t)$ denotes the left-over capacity available to departure traffic. (4.11) expresses the runway fundamental diagram; (4.12) determines the departure traffic flow; (4.13) simply states that, due to the high priority and free-flow condition for arrival traffic, the flow from the runway into the taxiway network is the same as the arrival flow (assuming that the time on the runway is negligible).

3) Hybrid CTM of apron traffic flow

Apron cells can be categorised into apron taxiing cells and stand cells. The latter is the destination of inbound flights and the origin of outbound flights; therefore, they are treated as both sink and source cells. Due to the highly complicated configuration of stands and taxiing routes within the apron area, a mesoscopic modelling approach by ignoring some fine granularities is employed as follows. Firstly, different stands into sink/source cells $j+1,\dots,j+n$ according to their spatial proximity and routing information is aggregated. Then the apron taxiways into cells $i+1,\dots,i+n$ is partitioned, which are then connected to the aggregated sink/source cells; see Figure 4.7. Using the notion of aggregate since and source cells, their sending and receiving capacities may be defined as usual, based on the physical characteristics of taxi links, flight schedules, and the occupancy of stands. These modelling details are omitted here.

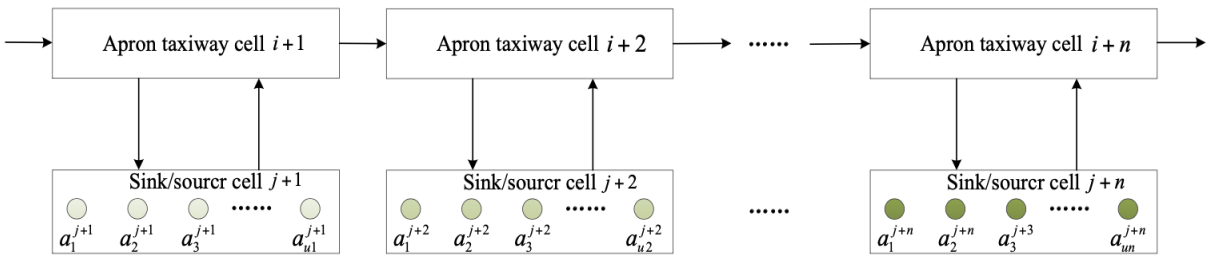

Figure 4.7. Cell representation of the apron area

4.3. CELLULAR AUTOMATA FOR AIRPORT SURFACE

4.3.1. Introduction

Cellular Automata (CA) is a computationally efficient microscopic model based on automata theory, which was established by John von Neumann and Stanislaw Ulam in the 1940s-1950s, and has widely been used in various fields, such as physics, microstructure modelling, theoretical biology (Maerivoet and De Moor, 2005). Four main ingredients play a key role in a CA model: the physical environment, the state of cells, the cell's neighbourhoods, and the transition rule.

A CA model consists of a discrete lattice of cells with the same topology (e.g., rectangular, triangular, isometric, hexagonal). The cells are typically homogenous and are equal in size, where the size of the lattice itself can be either infinite or finite, and the dimensionality of that can be in any finite number (e.g., the CA in one dimension is called an elementary cellular automaton, two dimensions is a grid, or other more dimensions in a Euclidean space) (Maerivoet and Moor, 2005). Each cell has a set of fixed "neighbourhoods", and that has finite states (e.g., on and off). The transition rule is defined and applied to all cells (a cell and its neighbourhood cells) in parallel. The state of cells changes at each discrete time step simultaneously, and the new state of cells is determined by that of itself and all direct neighbourhoods.

The Nagel-Schreckenberg model is a typical stochastic CA model, commonly known for the simulation of road traffic flow developed by Kai Nagel and Michael Schreckenberg (Nagel and Schreckenberg, 1992). This CA traffic model is able, in an efficient computation time, to capture the state of each vehicle at each time step and characteristics of dynamic traffic flow (e.g. traffic jam) both at microscopic and macroscopic scale. Similar to road traffic, the Cellular Automata Model for Airport surface (A-CA) model is an adaptation and refinement of the Nagel-Schreckenberg model for road traffic. The basic components of the N-S model are employed to describe the fundamental movement of the aircraft in the taxiway network, and a series of additional constraints and specifications are introduced to accommodate the highly

complex layout and surface movement on the airport. Due to space limitation, only a brief overview of the model is provided, while referring the reader to Sanchez (2019) for full details.

4.3.2. A-CA Modelling

This proposed A-CA model is based on Nagel-Schreckenberg model for road traffic. The basic components of the N-S model are employed to describe the fundamental movement of the aircraft in the taxiway network, and a series of additional constraints and specifications are introduced to accommodate the highly complex layout and surface movement at the airport.

4.3.2.1 Taxiing model

In the ACA model, each link is represented as a 1-D array of cells. The new position of the aircraft is updated at each time step and is expressed as:

$$x_i(t+1) = x_i(t) + v_i(t)$$

Each aircraft follows a given path connecting its origin and destination, where the route is comprised of a series of links and curves (nodes). The speed of each aircraft is determined jointly by several factors (e.g. preceding aircraft, curve, queuing, conflict), and is expressed as the minimum of several speeds:

$$v(t) = \min\left(v^{\text{unimpeded}}, v^{\text{curve}}, v^{\text{seperation}}, v^{\text{queuing}}, v^{\text{conflict}}\right)$$

In this thesis, the dimension of the cell is 5m, and the discrete time step is 5s. According to operation rules, the maximum taxiing speed is set at 20 knots while the speeds at turns (curves) and aprons are limited to 10 knots. Previous work by Gong (2009) indicates that an acceleration and deceleration around 0.2 $\mathrm{m/s^2}$ is applicable to most taxiing situations. The table below summarises the basic model parameters.

The following scenarios are further considered when determining aircraft speed and acceleration.

- **Curves and crossings.** Aircraft must conduct smooth deceleration when approaching a curve so that they do not exceed v^{curve} while turning. A deceleration rule is applied for aircraft approaching a curve or when there are obstacles ahead (e.g. conflicts).
- **Aircraft following and minimum separation.** The safety separation rule is applied for two or more aircraft taxiing along the same straight path. The separation requirement varies depending on the category of both leading and trailing aircraft (Yang et al., 2017).

4.3.2.2 Runway queuing model

Aircraft usually stop and wait for ATC clearance at the holding point prior to the entrance of the runway. When there is a non-zero departure queue, the aircraft needs to line up and to maintain minimum separation (50 m) with other aircraft in the queue. The deceleration rule is employed to control the speed of the aircraft when approaching the holding point or the end of the queue.

Due to limited runway capacity for departures, a minimum time headway h_{takeoff} is enforced between two consecutive takeoffs. Furthermore, as the runway is used for take-off, landing, and crossing, a minimum time separation h_{land} is maintained between a takeoff and landing. Additionally, an aircraft must have vacated the runway after landing before a departure to be given clearance, the duration of the landing run is denoted $h_{\text{exit ramp}}$. The following inequalities must hold for a queuing aircraft to be given clearance at time t:

$$t > t_{\text{previous takeoff}} + h_{\text{takeoff}} \tag{4.14}$$

$$t + h_{\text{land}} < t_{\text{next landing}} \tag{4.15}$$

$$t > t_{\text{previous landing}} + h_{\text{exit ramp}} \tag{4.16}$$

4.3.2.3 Conflict resolution

A conflict can occur when the trajectories of two aircraft overlap; the cells that form part of a node can only be occupied by one aircraft at any time, other aircraft not given priority to pass need to decelerate and wait for the node is clear and it is given permission to move again. The deceleration rule developed in Section 4.3.2.1. is employed.

To accommodate various conflict scenarios and resolution rules, the state of a node is defined, where conflicts may arise as:

State 0: the node is not occupied by any aircraft;

State 1: the node is occupied, with two sub-cases: (1) the aircraft is on the node; (2) the aircraft is not yet on the node, but given its speed will eventually end up on the node even with maximum deceleration;

State 2: the node is not occupied but still within the jet blast range of an aircraft that just leaves the node.

Given these states, sophisticated conflict resolution mechanisms are defined corresponding to the state transition patterns illustrated in Figure 4.8. Due to space limitations, these sub-cases are not elaborated here.

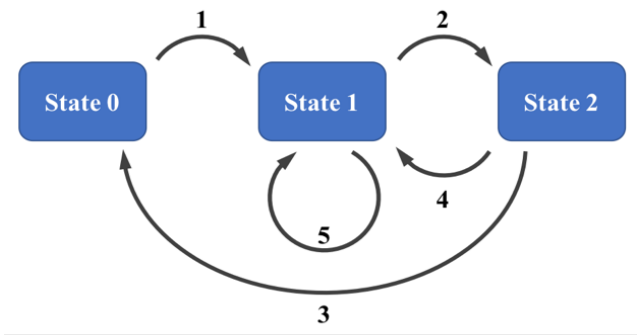

Figure 4.8. State transitions at a node (adopted from Sanchez (2019))

In principle, conflicts are resolved on a First-Come-First-Served (FCFS) basis. Although this is not always the case during airport taxiing, this approach has been taken to keep the simulation within reasonable complexity limits. In addition, beyond the scope of FCFS (e.g. when two aircraft are waiting simultaneously for clearance), priorities or preferences are established as follows:

- Arrivals over departures;
- Larger aircraft over smaller ones;
- Departures with a delay over a given threshold are given priority; and
- Aircraft that have been held at a node for over a given threshold are given higher priorities.

4.4. SUMMARY

This chapter has discussed the state-of-the-art in traffic dynamics on the airport surface network, by first elucidating traffic flow characteristics and dynamics. Based on these dynamic characteristics, typical traffic network models, namely the mesoscopic Cell Transmission Model (A-CTM) and the microscopic Cellular Automata model (A-CA) have been respectively reviewed. This microscopic simulation model A-CA is to be adopted in question, and is to be set up and calibrated using empirical data from PEK airport in Chapter 6. The calibrated model serves as the main simulation platform for validating the proposed optimisation solutions and for comparison purposes.

After introduction and review from the existing studies and projects, a framework for integrated apron-runway (origin-destination, or O-D) assignment (IARA) for aircraft movement on surface networks is presented in Chapter 5, to optimise surface operation on a pre-tactical level from the network optimisation perspective, which is the first stage of the proposed integrated and joint optimisation of runway-taxiway-apron.

CHAPTER 5 INTEGRATED APRON-RUNWAY ASSIGNMENT FOR AIRPORT SURFACE OPERATIONS

This chapter proposes a framework for integrated apron-runway (origin-destination, or O-D) assignment (IARA) for aircraft movement on surface networks, while considering various physical and operational constraints, such as runway and apron assignment rules, airport and airline preferences, TMA constraints, surface network topology, runway and apron congestion, and taxiing dynamics. A novel iterative apron-runway assignment method with embedded lexicographic and congestion-aware optimisation techniques is proposed, which is also able to handle temporal uncertainties using a data-driven robust approach. The proposed IARA aims to achieve the optimal spatial-temporal distribution of airside traffic demands, in such a way that significantly reduces required taxiing distances, with the added benefits of shorter taxiing time, fewer conflicts, reduced runway queuing and increased gate assignments.

The premise is that the apron and runway are no longer pre-determined for each aircraft as either origins or destinations; instead, they are re-configured to maximise the utilisation of airport network capacity in space and time. Their spatial re-distribution, as proposed in this thesis, would impact a number of surface operations including off-block control, taxi routing, and runway sequencing. These operations are not within the purview of this thesis, as no specific treatment is made towards them beyond default and straightforward choices. This allows us to demonstrate the effectiveness of the proposed apron-runway assignment even without any further optimisation to other related operations.

A combination of quantitative (Sections 5.2&5.6) and qualitative (Sections 5.4&5.5) assessments is performed to model this proposed IARA framework. Details related to the modelling refer to each section.

5.1. PROBLEM SETTING AND ASSUMPTIONS

The proposed apron-runway assignment framework is mainly for strategic and pre-tactical planning. Here, the former refers to planning of regular services or operations 2-7 days in advance; the latter refers to the planning of operations one day in advance or right before the day of operation. For strategic planning, scheduled flight information (including aircraft type and scheduled times of arrival/departure) are given, and we do not assume schedule uncertainties. For pre-tactical planning, we consider schedule uncertainties, that is, random deviation of the Actual Landing Times (ALDTs) and Actual Take-off Times (ATOTs) from their scheduled counterparts, which this work intends to address with a robust approach. Abnormal circumstances such as flight cancelations or extreme weather are not within the scope of this research. However, they can be accommodated within the proposed framework by ad hoc operational rules designed to handle abnormal circumstances.

In this section, the following assumptions are made.

Assumption 1. The taxiway network (including runways and aprons as nodes) is treated as a graph with unidirectional links. Detailed aircraft movement within the apron area is not considered in this thesis; instead, potential delays caused by congestion within the apron are modelled using a macroscopic relationship between apron occupancy, geometry, and capacity.

Assumption 2. The apron-runway assignment problem is conceived in a pre-tactical decision environment. It is assumed that the runway of each arrival aircraft is determined by air traffic control, which is exogenous to this work. Each departure aircraft is assigned a unique runway by an algorithm proposed in this work. In addition, on a pre-tactical level, the Scheduled Times of Arrival (STAs) and Scheduled Times of Departure (STDs) are given as exogenous inputs of this work. Possible deviations of Actual Landing Times (ALDTs) and Actual Take-off Times (ATOTs) from the STAs and STDs, as often observed in real-time operations, are accounted for by a data-driven robust approach. The robust approach considers a reasonable range of

parameter uncertainties and aims to optimise the system's performance under the worst-case scenario.

Assumption 3. For connecting flights, if the turn-around time exceeds a certain threshold or when it needs to switch from a domestic (international) to an international (domestic) stand, the aircraft is towed to a different apron. As aircraft towing involves many ad hoc operations, which are beyond the modelling scope of this work, thus, two connecting flights are assumed to always share the same apron and stand.

5.2. PROBLEM DEFINITION AND FORMULATION

This methodology starts with introducing the following notations.

$[0, T]$:	operational horizon
F:	set of flights
F_1, F_2, F_3, F_4:	set of flights of Category 1 (super heavy), 2 (heavy), 3 (medium) and 4 (light), respectively
F^{Dep}, F^{Arr}:	set of departure and arrival flights, respectively
F^I, F^D:	set of international and domestic flights, respectively
F^S, F^C:	set of single and connecting flights, respectively
$F^{\bar{C}}$:	Set of connecting flights with distinct domestic/international status
Ω:	set of aprons
Ω^I, Ω^D:	set of aprons with international and domestic bridge stands, respectively
Ω^B, Ω^R:	set of aprons with bridge and remote stands, respectively

Λ:	set of runways
$N_1^\omega, N_2^\omega, N_3^\omega, N_4^\omega$:	number of Category 1, 2, 3 and 4 stands in apron $\omega \in \Omega$
$\mathrm{AIBT}_f, \mathrm{AOBT}_f$:	Actual in-block time and actual off-block time of flight f
$\mathrm{STA}_f, \mathrm{STD}_f$:	Scheduled Time for arrivals and scheduled time for departures of flight f

Definition (Single and connecting flights). Flight $f \in F$ is called a *single departure (arrival) flight* if it does not have a former (next) flight within the operational horizon. Two flights f_1 and $f_2 \in F$ are called *connecting flights* if $f_1 \in F^{Arr}$, $f_2 \in F^{Dep}$, and f_1 is the former flight of f_2, in which case are denoted as $f_1, f_2 \in F^C$, $f_1 \sim f_2$. If the connecting flights f_1, f_2 have distinct domestic/international status, they are denoted as $f_1, f_2 \in F^{\bar{C}}$.

The *dwell interval* of any single flight $f \in F$ is denoted as:

$$\tau(f) = \begin{cases} [\mathrm{AIBT}_f\ , T] & f \in F^S \cap F^{Arr} \\ [0\ , \mathrm{AOBT}_f] & f \in F^S \cap F^{Dep} \end{cases} \tag{5.1}$$

and the dwell interval of a pair of connecting flights $f_1 \sim f_2$ is denoted as

$$\tau(f_1) = \tau(f_2) = [\mathrm{AIBT}_{f_1}\ , \mathrm{AOBT}_{f_2}] \tag{5.2}$$

In other words, $\tau(f)$ or $\tau(f_1), \tau(f_2)$ are used to indicate the time intervals during which the corresponding flight occupies a stand.

In a pre-tactical decision environment, however, the AIBTs and AOBTs are not known in advance, and considerable deviation from their scheduled times can be observed from empirical data. Such uncertainties are represented by two random variables ε^{Arr} and ε^{Dep}, such that

$$\tau(f) = \begin{cases} \left[\mathrm{STA}_f + \varepsilon^{Arr}, T\right] & f \in F^S \cap F^{Arr} \\ \left[0,\ \mathrm{STD}_f + \varepsilon^{Dep}\right] & f \in F^S \cap F^{Dep} \end{cases}, \qquad (5.3)$$
$$\tau(f_1) = \tau(f_2) = \left[\mathrm{STA}_{f_1} + \varepsilon^{Arr}, \mathrm{STD}_{f_2} + \varepsilon^{Dep}\right]$$

Such uncertainties are handled via a data-driven approach in this solution scheme such that the resulting apron-runway assignment is robust against random deviations from scheduled times.

To facilitate mathematical formulation of the problem, the characteristic function is further defined as:

$$\chi_{[a,b]}(t) = \begin{cases} 1 & \text{if } t \in [a,b] \\ 0 & \text{otherwise} \end{cases} \qquad (5.4)$$

where $[a,b] \subset [0,T]$ is a given time interval within the operational horizon.

Apron-runway assignment problem on an airport surface is then stated as follows.

Determine runway $\lambda_f \in \Lambda$ and apron $\omega_f \in \Omega$ of every flight $f \in F$, in order to minimise the taxiing distances of all the flights:

$$\min\left[\mathcal{D}\left(\lambda_f, \omega_f\right): f \in F\right] \in \mathbb{R}^{|F|} \qquad (5.5)$$

such that

$$\omega_f \in \Omega^I \cup \Omega^R \quad \forall f \in F^I \cup F^{\bar{C}} \qquad (5.6)$$

$$\omega_f \in \Omega^D \cup \Omega^R \quad \forall f \in F^D \cap \left(F^S \cup F^C \setminus F^{\bar{C}}\right) \qquad (5.7)$$

$$\sum_{k=1}^{K} \left(\sum_{f \in \left(F^S \cup F^C \cap F^{Arr}\right) \cap F_k,\ \omega_f = \omega} \chi_{\tau(f)}(t) \right) \leq \sum_{k=1}^{K} N_k^{\omega} \qquad (5.8)$$

$$\forall K = 1,2,3,4, \forall t \in [0, T], \forall \omega \in \Omega$$

$$\omega_{f_1} = \omega_{f_2} \quad \forall f_1, f_2 \in F^C, f_1 \sim f_2 \tag{5.9}$$

$$\lambda_f = \bar{\lambda}_f \quad \forall f \in F^{Arr}, \ \lambda_f \in \Lambda_f \quad \forall f \in F^{Dep} \tag{5.10}$$

$$\text{following the assignment rules (a)-(i) and (o)-(q)} \tag{5.11}$$

In (5.5), $\mathcal{D}(\lambda_f, \omega_f)$ is the network distance from λ_f to ω_f if $f \in F^A$, or from ω_f to λ_f if $f \in F^D$. The objective (5.5) minimises the taxiing distances of all the flights. Equations (5.6) and (5.7) together express apron allocation constraints (j), (m) and (n). Equation (5.8) is a compact expression of constraints (k) and (l). Equation (5.9) indicates that two connecting flights share the same apron, as aircraft towing operations are not considered in the search. In Equation (5.10), $\bar{\lambda}_f$ is the runway assigned to arrival flight $f \in F^{Arr}$ by ATCO during the approaching process, which is exogenously determined; $\Lambda_f \subset \Lambda$ denotes the subset of runways that can be assigned to departure flights $f \in F^{Dep}$. In real-world operation, Λ_f depends on the flight category and destination; more details are presented in the runway assignment rules (o)-(q). Finally, the optimal apron-runway assignment problem is further guided by the preference rules shown in (5.11).

The proposed apron-runway assignment problem (5.5)-(5.11) is an unconventional combinatorial optimisation problem, in that it has embedded preference rules for aircraft-apron-runway assignment that are qualitative in nature. To effectively solve this problem while considering non-mathematical assignment rules and preference orders, in the remainder of this chapter, a mixed qualitative-quantitative methodology is employed, as outlined in Section 5.3.

5.3. METHODOLOGICAL FRAMEWORK

The framework for the optimisation of apron-runway assignment consists of the following steps, which are also illustrated in Figure 5.1.

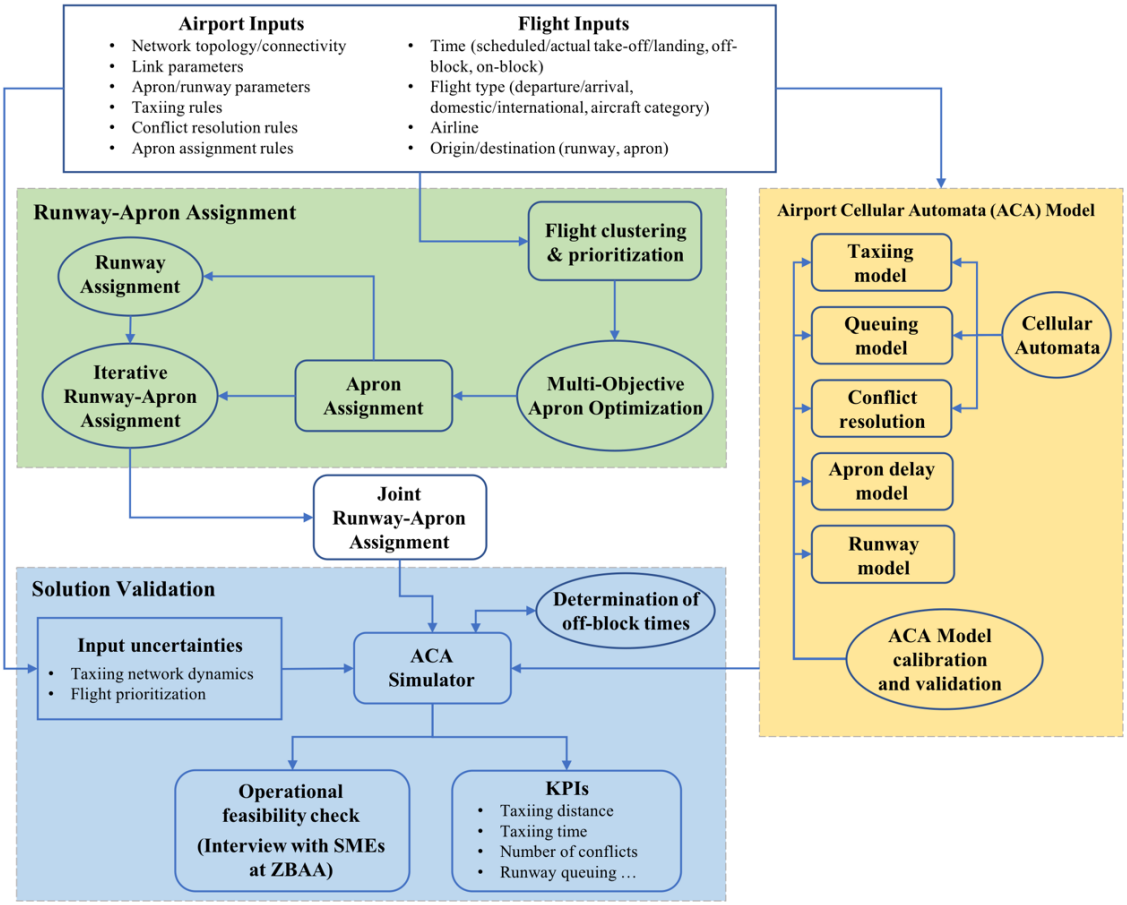

Figure 5.1. Overall methodology of the proposed IARA

1. **Flight clustering**. Based on the apron assignment rules (Section 5.4) generated from interviews with SMEs, flights that share certain attributes into clusters are grouped.
2. **Inter- and intra-cluster ranking**. The clusters are ranked according to their priorities based on their defining attributes (inter-cluster ranking), which is achieved based on

interviews with SMEs (Section 5.5). Flights within a given cluster are further ranked (randomly) to facilitate the lexicographic multi-objective optimisation of apron/runway assignment (intra-cluster ranking). Flight clustering and ranking are elaborated in Section 5.5.

3. **Multi-objective apron assignment**. The methodology is started with an apron assignment by fixing the runway information of all flights. To accommodate the multi-objective nature and embedded preference structure of the problem, a lexicographic optimisation approach is employed by sequentially solving a series of single-objective optimisation problems with updated constraint sets.
4. **Multi-objective runway assignment**. Once the aprons are allocated and fixed for all the flights, a similar lexicographic optimisation approach is employed for runway assignment.
5. **Iterative apron-runway assignment**. Steps 3 and 4 are repeated until no changes are made in the apron and runway allocation for all the flights within a full iteration. The resulting assignment is taken as the final output.
6. **Simulation test**. The proposed new runway and apron allocation is tested by microscopic simulation, namely the Airport Cellular Automata (ACA) model. The conventional cellular automata model is extended to treat taxiing and queuing dynamics, conflict resolution, apron delay and runway dynamics. The detailed ACA model is presented in Section 4.3.2. Several input uncertainties are incorporated to produce a range of possible outcomes for a number of key performance indicators, including taxiing distance and time, number of conflicts, and runway queuing.
7. **External validation**. The operational feasibility and viability of the proposed apron-runway assignment framework are assessed through interviews with subject matter experts at PEK.

The detailed technical flow chart for the apron-runway assignment methodology is presented in Figure 5.2.

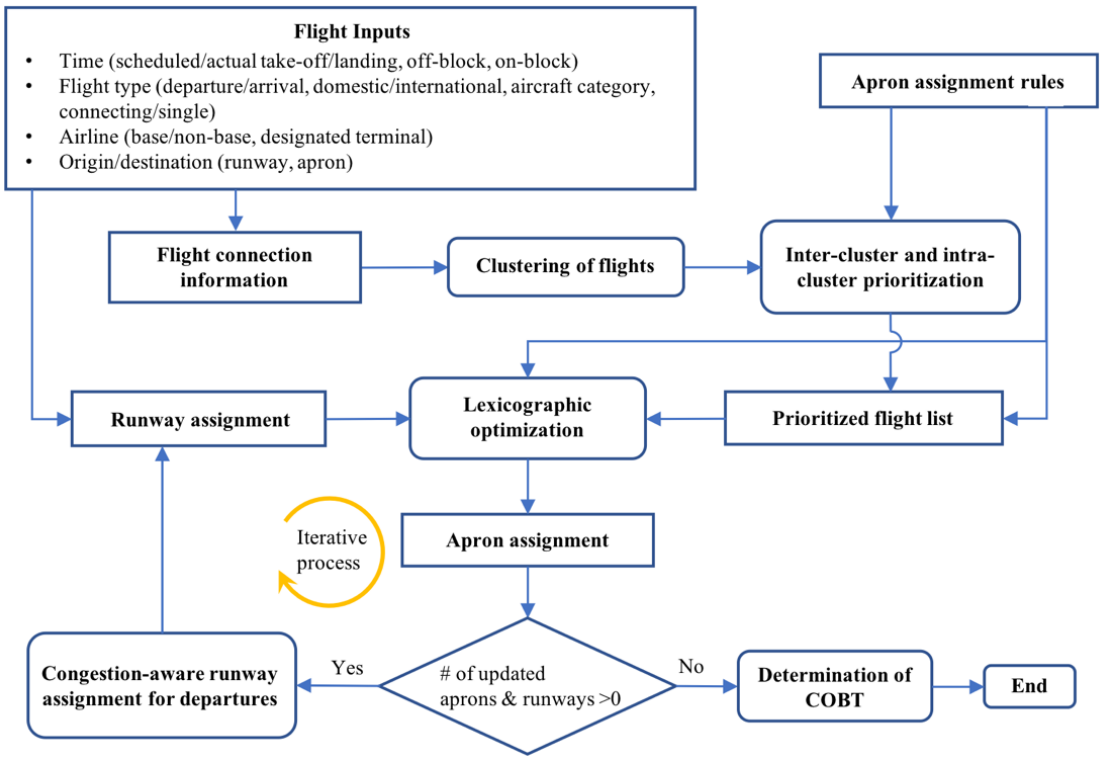

Figure 5.2. Flow chart of the proposed joint apron-runway assignment

5.4. APRON AND RUNWAY ASSIGNMENT RULES AND CONSTRAINTS

The following apron assignment rules are derived from the Operational Manual of PEK and confirmed by SMEs. In general, this is achieved in two stages. During the first stage, review relevant literature to gain critical understandings of rules, and constraints should be considered in the model, which included a review of academic studies (see Section 3.2) and operation-related documents from airports and regulatory bodies of SESAR, NextGen (Section 3.1). Based on these reviews, the second stage involves a series of semi-structured face-to-face interviews using a questionnaire (see Section 5.4) in the first round of interview (see Section

1.3.1). This questionnaire aimed at capturing rules, constraints, and preferences of each component, i.e., runway and apron, as well as identifying current operational deficiencies. As a result of the interview and guidance from the Operational Manual, relevant rules, constraints, and preferences are derived and summarised as follows, which were confirmed by SMEs.

5.4.1. Questionnaire Design

The questionnaire was designed according to the following criteria (Oppenheim, 2000):

1. Selected questions should be clear and representative to capture the nature of each operational characteristics.

2. The ability of open-ended questions (as opposed to finite multiple-choice answers) to engage respondents in dialogue, provide specifics on each characteristic, specific examples, and their thoughts on how to improve the current operation.

This questionnaire was designed to capture the operational context of airport surface characteristics, while seeking to extract relevant rules, constraints and preferences concerning runway, taxiway, and apron operations. The primary purpose of the questionnaire was to initiate a discussion of operational characteristics on airport surface in a structured way. The interviewer was then able to gain a deeper knowledge of current operations, the logic behind various efforts, and any flaws in current operations that needed to be addressed. For example, a question such as "what characteristics should be considered in stand assignment?" attempts to identify specific attributes that should be considered while performing stand assignment in real-world operation. Moreover, the open questionnaire format allowed for further discussion with the interviewee in order to yield additional operational insights; for example, "is it feasible for ATCOs to follow the dynamic taxiing route on the airport surface? What if an auto-system with real-time taxiing route guidance is provided?".

Apron and runway operations are typically performed by different stakeholders. For example, an air controller at PEK may be unaware of the processes of stand allocation, which is performed by a stand allocator. Given the complexity of airport surface operation, the criteria

for selecting SMEs include their work experience in runway and stand operations, variability of their perspective, and the tendency to view surface operations in a holistic manner.

To meet these criteria, eight SMEs were selected, with 10 years of working experience in in the aviation field and the relevance of their specialisation on average. The interviewees are involved in the operational management at the PEK, among which, one is the duty manager of the Airport Operation Centre (AOC), one is responsible for airside resource assignment, three specialises in stand allocation and three ATCOs specialise in runway management.

The purpose of this interview was to identify and confirm the rules, constraints, and preferences of runway, taxiway, and apron that should be considered based on a comprehensive review of the literature, while performing an integrated operation of runway and apron assignment. Furthermore, these SMEs also attend the questionnaire survey in the second round (see Section 5.5).

5.4.2. Questionnaire and Response

In this section, the results of the free Q&A interview sessions are presented. For brevity, the answers of the interviewees are summarised as follows:

Question 1: What characteristics should be considered in stand assignment prioritisation?

Answer 1: Aircraft types (domestic or international, passenger or cargo), operational types (arrival or departure), aircraft categories (small, medium, heavy, super heavy), airlines (base airlines or non-base airlines), flight status (connecting or single).

Question 2: Are there rules or preferences for stand prioritisation?

Answer 2: In general, different stand planners have their own preferences and experiences, though fundamental rules for stand prioritisation should be considered while assigning, which are summarised as follows.

1) Larger aircraft over smaller aircraft (i.e. super heavy > heavy > medium > light);

2) Base airlines over non-base aircraft;

3) Connecting aircraft over single aircraft;

3) International aircraft over domestic aircraft;

4) Passenger aircraft over cargo aircraft;

5) Single departure over single arrival;

6) Connecting aircraft with shorter scheduled turn-around time over those with longer scheduled turn-around time;

7)Bridge stands over remote stands;

8)Aircraft with emergency over normal aircraft; and

9)Aircraft with VIP over normal aircraft.

Question 3: What do connecting flights stands for, and how is it possible to distinguish connecting flights from a single flight?

Answer 3: Two flights operated by the same aircraft (with the same flight registration), transiting at an airport are considered connecting flights. For example, if an arrival flight with the registration number of B1234 arrives at PEK at 9.00 am, and a departure flight with the same registration, departs from the PEK at 11.00 am, they are considered connecting flights.

Question 4: Are there any rules for stand allocation?

Answer 4: While assigning, apron category, aircraft category, the aircraft type, dwell time, flight type should be considered. In particular, if the flight is assigned to a bridge stand, it should be assigned to its airlines' corresponding aprons, for example, Hainan Airlines (domestic) is located at terminal 1 in PEK, whereas Air China Airlines is located at terminal 3. In addition, for base airlines, contact stands are preferred. However, if no available contact stands, remote stands close to the bridge stands would be preferred.

Question 5: Does PEK make an assignment plan on a pre-tactical level?

Answer 5: Yes, both stand and runway assignments are planned on a pre-tactical level. However, these assignments are planned separately, i.e., the gate is assigned by stand operators, while the runway is assigned by ATCOs, coming from different institutions. Normally the resulting assignment with the same flight plan is unchanged.

Question 6: What is the prioritisation between bridge and remote stands?

Answer 6: In general, base airlines prefer to be assigned to contact if available. Contact stands not only enhances passengers' satisfaction, but also make the airport profitable. In addition, the number of gate assignments is a metric used in assessing airport or airline service quality. On the other hand, budget airlines may prefer to be assigned to remote stands for the purpose of saving operational cost.

Question 7: Is it possible to assign a domestic flight to an international stand, or vice versa?

Answer 7: In general, this is not allowed at PEK because international and domestic stands are operated separately; the usage of International stands should follow the policy of customs and immigration. If corresponding bridge stands are not available, remote stands would be preferred. In some special cases, for example, connecting flights with distinct flight types (an international arrival flight segment followed by a domestic departure flight segment), this aircraft may be assigned to an international stand under the permission of customs and immigration. In doing so, passengers in the first arrival flight segment aircraft can disembark via a jet bridge, while in the second departure flight segment, this stand is used as a remote stand, though it is connected to the terminal, where passengers should be transferred via a shuttle bus or walking guidance from the terminal to the aircraft.

Question 8: Is there any suggestion of a stand assignment of connecting flights with distinct flight types, for example, a domestic arrival flight followed by an international departure flight, or vice versa?

Answer 8: For connecting flights with distinct flight types, if the scheduled turn-around time is sufficient (usually more than 2.5 hours), the domestic arrival flight may be assigned to a domestic bridge-stand (if bridge-stand is available) first. When the after-flight service is finished, this aircraft may be towed to an international stand. On the other hand, if the scheduled turn-around time is limited, the international stand may be chosen with the permission of the custom and immigration, otherwise, this aircraft may be assigned to a remote stand.

On the other hand, if an international arrival flight is followed by a domestic departure flight, the first flight is an international arrival aircraft, this aircraft may be assigned to an international bridge-stand in the first flight period (international arrival). In the second flight period (domestic departure), this international stand may be treated as a remote stand, taking passengers from the terminal to the aircraft by a shuttle bus or walking guidance. This activity also should be with the permission of customs and immigration. Otherwise, a remote stand may be used.

Question 9: In empirical flight data, there are connecting flights with long-scheduled turn-around time, for example, the first flight segment arrives at PEK in the morning and the second flight segment departs from PEK in the afternoon, or even later. Will these flights be parking at their origin contact stands for such a long time period (i.e. an entire turn-around time)? May this case reduce the stand utilisation?

Answer 9: Connecting flights with a long transit time may lose the priority of being located at a bridge-stand for an entire transit time period. In general, if the transit time is over 4.5 hours, the aircraft is assigned to a remote stand directly or assigned to a bridge-stand first, and then towed to a remote stand while the post-flight service is finished. However, if the flight still needs to get the passengers via the jet bridge, the stand operator would assign a new bridge-stand to this flight at the appropriate time. In this case, from the perspective of stand allocation, these connecting flights may be considered as two independent flights, though they are with the same flight registration, since stands are assigned in arrival and departure time period, respectively.

5.4.3. Rules and Constraints Used in the Model

Based on the above interview, along with the Operational Manual of PEK, the rules, constraints, and preferences of runway and apron allocation are derived and summarised as follows, which also confirmed by SMEs.

Note that A>B means A receives a higher priority than B.

(a) Bridge stands are preferred over remote stands during apron assignment;

(b) Aircraft should be assigned to aprons/stands as close as possible to the terminal where the airline is based;

(c) The apron/stand assigned to departing aircraft should be as close as possible to the assigned runway;

(d) Connecting flights > single departure > single arrival for bridge stand allocation;

(e) Connecting flight with smaller dwell time > connecting flight with larger dwell time for bridge stand allocation;

(f) Larger aircraft > smaller aircraft for bridge stand allocation;

(g) Base airlines > non-base airlines;

(h) International flights > domestic flights;

(i) Passenger flights > cargo flights;

Items (a)-(c) are concerned with the priority of aprons and runways during assignment; (d)-(i) express the relative priorities of different flight types, with the full list of prioritised flight types presented in Section 5.5.

The following apron/stand assignment constraints/rules are considered in this research:

(j) International (domestic) flights can only be assigned to international (domestic) bridge stands or any remote stands, with the exception in (n) below;

(k) A stand can be occupied by at most one aircraft at a time;

(l) The stands have four categories: Category 1 (super-heavy), Category 2 (heavy),

Category 3 (medium), and Category 4 (light). An aircraft can only be assigned to stands with the same or larger categories; an aircraft can be assigned to a larger stand only when there are no stands available with matching category;

(m) For two connecting flights with the same domestic/international status, they are assigned to the same stand;

(n) For two connecting flights with distinct domestic/international status, an international bridge stand is preferred, in which case the domestic leg is accommodated with a shuttle service. In the absence of an available international bridge stand, a remote stand is assigned;

The runway assignment rules are considered as below:

(o) Departing demand should be distributed to runways evenly, without causing significant congestion at any particular runway at a given time;

(p) Each flight has a given set of runways it can be assigned to, according to its category and destination; and

(q) The runway assigned to a departing aircraft should be as close to the apron as possible.

5.5. PRIORITISATION OF FLIGHT CLUSTERS

To obtain the prioritisation of flight clusters, the second round of interview with a questionnaire survey was performed (see Section 5.5.1). Five interviewees who attended the first round, with 11 years of working experience on average and specialising in apron assignment and airside operations, were selected for the second round. The details of each interviewee and their response are shown in Section 5.5.2.

5.5.1. Questionnaire Design

Five attributes are defined that are relevant to apron or runway assignment summarised in Section 5.4. These attributes include flight type (domestic or international, passenger or cargo), operational type (arrival or departure), aircraft category (Category 4-light, Category 3-medium, Category 2-heavy, Category 1-super heavy), airline, flight status (single or connecting), and turn-around time. The real-time world data collected from PEK throughout a 24-hr operational horizon are then grouped into 20 clusters after omitting unrealistic combination.

The relevance and importance of these attributes, as well as the relative priorities of the 20 flight clusters, are confirmed by interviews with the SMEs. This questionnaire survey aims to gain priority ranking of the 20 cluster groups to be considered later in the mathematical optimisation model. The questionnaire details are as follows.

INTRODUCTION: please give a rank for the following 20 flight clusters. For example, 1>2>3 indicates that the priority of the cluster 1 is higher than cluster 2 and is higher than cluster 3. Please note that, only rigid indicators and allocation preferences are considered, and the result is only to be used for academic research for stand allocation.

Flight Cluster	Aircraft Type
1	Connecting, International, Base airlines, Super Heavy
2	Connecting, International, Base airlines, Heavy
3	Connecting, International, Non-base airlines, Super Heavy
4	Connecting, International, Non-base airlines, Heavy
5	Connecting, International, Base airlines, Medium/Light
6	Connecting, International, Non-base airlines, Medium/Light
7	Connecting, Domestic, Base airlines, Super Heavy
8	Connecting, Domestic, Base airlines, Heavy
9	Connecting, Domestic, Non-base airlines, Heavy
10	Connecting, Domestic, Base airlines, Medium/Light
11	Connecting, Domestic, Non-base airlines, Medium/Light

12	Single departure, International, Heavy
13	Single departure, International, Medium
14	Single arrival, International, Heavy
15	Single arrival, International, Medium/Light
16	Single departure, Domestic, Heavy
17	Single departure, Domestic, Medium/Light
18	Single arrival, Domestic, Heavy
19	Single arrival, Domestic, Medium
20	Cargo flights

5.5.2. Response of the Questionnaire

The purpose of this questionnaire is to All five interviewees are involved in the operational management at the Beijing International Airport, among which, one is the duty manager of the Airport Operation Centre (AOC), one is responsible for airside resource assignment, and three specialises in stand allocation. This survey consists of two procedures. First of all, five SMEs answer the questionnaires independently. Secondly, with a balanced consideration of their responses, the ranking of the 20 clusters agreed by all the SMEs with a group discussion, as well as their defining attributes.

The general information for each interviewee, along with the ranking suggestion in the independent answer stage, is shown as follows. The final ranking results are shown in Table 5.1. In which, 'Connecting' refers to a pair of flights. In the case that the two connecting flights have different domestic/international status, they are treated as 'International', according to apron assignment rule (n).

Interviewee 1: Airside Resource Director

Number of years: 13 years

Ranking suggestion:

1> 3>7> 2> 4> 8> 9> 5> 6> 10> 11> 12> 14> 13> 15> 16> 18> 17> 19> 20

Interviewee 2: AOC Duty Manager

Number of years: 12 years

Ranking suggestion:

1> 3> 7> 2> 4> 8> 9> 12>14> 5> 6> 9> 16> 18> 10> 11> 13> 15> 17> 19> 20

Interviewee 3: Senior Manager for Stand Allocation

Number of years: 9 years

Ranking suggestion:

1> 3> 7> 2> 4> 8> 9> 5> 6> 10> 11> 12> 16> 13> 17> 14> 18> 15> 19> 20

Interviewee 4: Stand Allocation Supervisor

Number of years: 10 years

Ranking suggestion

1> 7> 3> 2> 8> 4> 9> 5> 10> 6> 11> 12> 14> 13> 15> 16> 18> 17> 19> 20

Interviewee 5: Stand Allocation Supervisor

Number of years: 11 years

Ranking suggestion

1> 3> 7> 2> 4> 8> 9> 5> 6> 10> 11> 12>13> 16> 17> 14> 18> 15> 19> 20

Table 5.1. Flight clusters (arranged in decreasing order of priority) and their defining attributes

1. Connecting, International, Base airlines, Super Heavy, Passenger	2. Connecting, Domestic, Non-base airlines, Super Heavy, Passenger
3. Connecting, Domestic, Base airline, Super Heavy, Passenger	4. Connecting, International, Base airlines, Heavy, Passenger
5. Connecting, International, Non-base airlines, Heavy, Passenger	6. Connecting, Domestic, Base airlines, Heavy, Passenger
7. Connecting, Domestic, Non-base airlines, Heavy, Passenger	8. Connecting, International, Base airlines, Medium/light, Passenger
9. Connecting, International, Non-base airlines, Medium/Light, Passenger	10. Connecting, Domestic, Base airline, Medium/Light, Passenger
11. Connecting, Domestic, Non-base airlines, Medium/Light, Passenger	12. Single departure, International, Heavy, Passenger
13. Single departure, International, Medium/Light, Passenger	14. Single departure, International, Heavy, Passenger
15. Single departure, Domestic, Medium/Light, Passenger	16. Single arrival, Domestic, Heavy, Passenger
17. Single arrival, Domestic, Heavy, Passenger	18. Single arrival, International, Medium/Light, Passenger
19. Single arrival, Domestic, Medium/Light, Passenger	20. Cargo flights

Remark 1. *Given Assumption 3, two connecting flights are always assigned to the same apron. Therefore, in subsequent ranking and apron assignment, a pair of connecting flights are treated as one entity.*

5.6. JOINT APRON-RUNWAY ASSIGNMENT

The apron-runway assignment is done in an iterative process that assigns aprons and runways alternately to individual flights, until certain convergence criterion is met. The detailed assignment process is elaborated in the sections below, with an overview of the O-D assignment process in Figure 5.2.

5.6.1. Lexicographic Approach for Apron Assignment

The multi-objective optimisation problem (5.5)-(5.10) aims to minimise the taxiing distances of all the flights within a 24-hr operational horizon, while meeting complicated and non-convex constraints. Additionally, the apron assignment rule dictates a preference structure for various types of flights. Therefore, a lexicographic optimisation approach is employed, which minimises the taxiing distance of individual flights in series according to their priorities. As the prioritisation result presented in Table 5.1 does not concern with individual flights, the flights within each cluster are further ranked randomly. Such intra-cluster ranking is randomised for two reasons: (1) there is no agreed criterion to further prioritise flights in the same cluster; and (2) by randomising intra-cluster rankings followed by independent random simulations, the impact of personal bias from apron allocators may be reduced and more robust apron-runway assignment results may be obtained.

The set of flights is sorted in a decreasing order of priority $\{\mathcal{F}_i, i = 1, \dots, M\}$, where $\mathcal{F}_i$ is a singleton or binary set: $\mathcal{F}_i = \{f_i\}$ or $\mathcal{F}_i = \{f_i^a, f_i^d\}$. In the former case, f_i is a single flight; in the latter case, f_i^a and f_i^d are connecting flights (the superscripts indicate 'arrival' or 'departure'). As two connecting flights share the same stand, they are treated as one entity in the flight ranking and apron assignment. The lexicographic optimisation solves the following sub-problems in series:

$$\text{Sub-problem } i\text{: } \min_{\omega_{\mathcal{F}_i}} \Phi\left(\omega_{\mathcal{F}_i}\right) = \begin{cases} \mathcal{D}\left(\lambda_{f_i}, \omega_{f_i}\right) & \text{if } \mathcal{F}_i = \{f_i\} \\ \mathcal{D}\left(\lambda_{f_i^a}, \omega_{f_i^a}\right) + \mathcal{D}\left(\omega_{f_i^d}, \lambda_{f_i^d}\right) & \text{if } \mathcal{F}_i = \{f_i^a, f_i^d\} \end{cases} \tag{5.12}$$

such that

$$\omega_{\mathcal{F}_i} \in \Omega_{\mathcal{F}_i} \doteq \begin{cases} \Omega^I \cup \Omega^R & \text{if } \mathcal{F}_i \subset F^I \cup F^{\bar{C}} \\ \Omega^D \cup \Omega^R & \text{if } \mathcal{F}_i \subset F^D \end{cases} \tag{5.13}$$

$$\sum_{k=1}^{K} \left(\sum_{j \le i,\, \omega_{\mathcal{F}_j} = \omega_{\mathcal{F}_i},\, \mathcal{F}_j \subset F_k} \chi_{\tau(\mathcal{F}_j)}(t) \right) \le \sum_{k=1}^{K} N_k^{\omega} \tag{5.14}$$

$$\forall K = 1,2,3,4, \forall t \in [0, T]$$

$$\text{subject to the preference rules (a)-(c)} \tag{5.15}$$

The objective (5.12) is to minimise the taxiing distance if $\mathcal{F}_i$ contains a single flight, or the combined taxi-in and taxi-out distances if $\mathcal{F}_i$ consists of a pair of connecting flights. This objective conforms to rule (c). Constraint (5.13) is equivalent to the apron assignment rules (5.6) and (5.7). Constraint (5.14) expresses the apron capacity constraint (5.8) subject to apron assignment already determined for $\mathcal{F}_1, \dots, \mathcal{F}_{i-1}$.

The sub-problem i above is stochastic since the dwell intervals $\tau(\mathcal{F}_j)$ in (5.14) is uncertain as shown in (5.3). To absorb the uncertainties in AIBTs and AOBT without significantly complicating the model, a data-driven robust approach is proposed by analysing the empirical distributions of the deviation of AIBT or AOBT from their respective scheduled times, i.e. STA and STD, which are available in a pre-tactical decision environment. The empirical distributions of the random variables ε^{Arr} and ε^{Dep} in Sep 2017 are shown in Figure 5.3, which contains over 20,000 data entries for each.

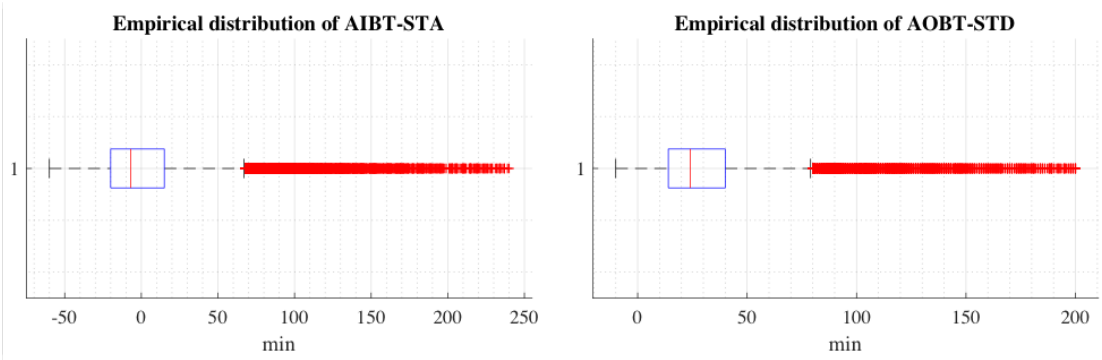

Figure 5.3. Empirical distributions of $\boldsymbol{\varepsilon^{Arr}}$ and $\boldsymbol{\varepsilon^{Dep}}$

The 25th and 75th percentiles are taken as the upper and lower bounds of ε^{Arr} and ε^{Dep}, as data beyond this range are likely caused by circumstances beyond normal operations (e.g. extreme weather conditions). Moreover, being overly conservative in formulating the uncertainty set has a negative effect on model performance (Goh and Sim, 2010). δ_1^{Arr} and δ_2^{Arr} (δ_1^{Dep} and δ_2^{Dep}) are set as the 25th and 75th percentiles of the distribution for arrivals (departures). Then, the dwell intervals are augmented with buffers as shown below:

$$\tau(\mathcal{F}) = \begin{cases} [\mathrm{STA}_f + \delta_1^{Arr}, T] & \mathcal{F} \subset F^S \cap F^{Arr} \\ [0, \mathrm{STD}_f + \delta_2^{Dep}] & \mathcal{F} \subset F^S \cap F^{Dep} \end{cases},$$
$$\tau(\mathcal{F}) = [\min(\mathrm{STA}_{f_1} + \delta_1^{Arr}, \mathrm{STD}_{f_2} + \delta_1^{Dep}), \max(\mathrm{STA}_{f_1} + \delta_2^{Arr}, \mathrm{STD}_{f_2} + \delta_2^{Dep})] \quad \mathcal{F} \subset F^C \tag{5.16}$$

In the case of Figure 5.3, $\delta_1^{Arr} = -20$, $\delta_2^{Arr} = 15$, $\delta_1^{Dep} = 14$ and $\delta_2^{Dep} = 40$ are set; then (5.16) becomes

$$\tau(\mathcal{F}) = \begin{cases} [\mathrm{STA}_f - 20, T] & \mathcal{F} \subset F^S \cap F^{Arr} \\ [0, \mathrm{STD}_f + 40] & \mathcal{F} \subset F^S \cap F^{Dep} \end{cases},$$
$$\tau(\mathcal{F}) = [\mathrm{STA}_{f_1} - 20, \mathrm{STD}_f + 40] \quad \mathcal{F} \subset F^C \tag{5.17}$$

To solve (5.12)-(5.16) while considering the assignment preferences, the following lexicographic algorithm is devised.

Algorithm 1 (Lexicographic apron assignment)

Input
1. Set of flights $\{\mathcal{F}_i, i = 1, \dots, M\}$ in descending order of priority;
2. The runway information for each flight;
3. For each $i = 1, \dots, M$, the set of aprons Ω_i^{BA} adjacent to the corresponding terminal where the airline is based;

Initialize $i = 1$

Step 1 Sort all aprons $\omega \in \Omega_{\mathcal{F}_i} \cap \Omega_i^{\mathrm{BA}}$ in ascending order of $\Phi(\omega)$, denote the sorted set by A;

Sort all aprons $\omega \in \Omega_{\mathcal{F}_i} \cap \Omega^B \setminus \Omega_i^{\mathrm{BA}}$ in ascending order of $\Phi(\omega)$, denote the sorted set by B;

Sort all aprons $\omega \in \Omega_{\mathcal{F}_i} \cap \Omega^R$ in ascending order of $\Phi(\omega)$, denote the sorted set by C;

Concatenate A, B, C to form the ordered set $X = A \oplus B \oplus C$

Step 2 Find the first element ω_0 in the ordered set X that satisfies constraint (5.14) and (5.16);

set $\omega_{\mathcal{F}_i} = \omega_0$.

Step 3 If $i = M$, the algorithm terminates; otherwise, $i = i + 1$, go to **Step 1**

Output Apron assigned to each flight

In algorithm 1, set A represents aprons that are adjacent to the terminal where the airline is based (a.k.a. base terminal); set B represents aprons containing bridge stands, which are not attached to the base terminal; set C represents all remote stands. According to assignment rule (a) and (b), the priority is $A > B > C$. Within each set, the aprons are further sorted according

to the distance from the runway $\Phi(\omega)$. Therefore, Step 2 finds the apron that is the closest to the runway (rule (c)) subject to rules (a) and (b), and constraint (5.14) makes sure that there are vacant stands available with the appropriate category for the dwell interval of the aircraft.

5.6.2. Congestion-aware Runway Assignment

After the apron assignment procedure, runway assignment for departures is performed. In this module, the aprons of all flights are known and fixed. Per runway assignment rule (p), each departing flight $f \in F^{Dep}$ has a subset of runways Λ_f that it can be assigned to. In addition, the assignment procedure should be aware of runway queuing and congestion, by distributing departures to all runways evenly during any given time window. This is done by devising the following objective function

$$\min_{\lambda=(\lambda_f:f\in F^{Dep})} \left[\mathcal{D}(\lambda_f\,,\omega_f) + w\cdot \mathcal{C}_f(\lambda;\bar{\lambda}): f \in F^{Dep}\right] \in \mathbb{R}^{|F^{Dep}|} \tag{5.18}$$

where the decision vector $\lambda = (\lambda_f: f \in F^{Dep})$ contains runway information for all departing flights; $\bar{\lambda} = (\bar{\lambda}_g: g \in F^{Arr})$ denotes the set of runways assigned to all arrival flights, which are exogenously determined. This is a multi-objective function, and for each flight f, the objective is to minimise the weighted sum of the taxiing distances $\mathcal{D}(\lambda_f\,,\omega_f)$ and a congestion cost function $\mathcal{C}_f(\lambda;\bar{\lambda})$ pertaining to runway queuing. In particular, the operational horizon is partitioned into time windows (e.g. 15 min each) $\{W_s: s = 1,2,\dots\}$, and write

$$\mathcal{C}_f(\lambda;\bar{\lambda}) = \left(\sum_{f'\in F^{Arr},\bar{\lambda}_{f'}=\lambda_f} \chi_{W_s}(\mathrm{STA}_{f'}) + \sum_{f'\in F^{Dep},\lambda_{f'}=\lambda_f} \chi_{W_s}(\mathrm{STD}_{f'})\right)^n \tag{5.19}$$

where W_s is such that $\mathrm{STD}_f \in W_s$; $n > 1$ is a parameter that introduces nonlinear congestion effect; the characteristic function $\chi_{W_s}(\cdot)$ is defined in (5.4). In prose, the summation within Equation (5.19) represents the total number of flights whose STAs (for arrivals) or STDs (for

departures) are within the same time window W_s as $f \in F^{Dep}$. Such a congestion function allows the weighted sum in (5.18) to balance between seeking the nearest runway and evenly distributing demands on all runways. Indeed, when the demand for departure is low within a given time window, the problem tends to minimise taxiing distances; when the demand increases, the function $\mathcal{C}_f(\lambda)$ dominates $\mathcal{D}(\lambda_f, \omega_f)$, and as a result avoids sending too many aircraft to a certain runway. The congestion function $\mathcal{C}_f$ also depends on the arrivals as runway usage is heavily influenced by scheduled arrivals with high priorities.

To solve the multi-objective optimisation problem (5.18) for runway assignment, a similar lexicographic optimisation approach is employed, by sorting the departure flights chronologically according to their STDs. The ordered set is denoted as $\{f_i, i = 1, \dots, |F^{Dep}|\}$. The i-th optimisation sub-problem reads:

$$\text{Sub-problem } i\text{: } \min_{\lambda_f} \mathcal{D}(\lambda_f, \omega_f) + w \cdot \bar{\mathcal{C}}_f(\lambda_f; \bar{\lambda}) \tag{5.20}$$

such that

$$\lambda_f \in \Lambda_f \;\; \forall f \in F^{Dep} \tag{5.21}$$

where Λ_f denotes the set of runways that can be assigned to departure flight f. In view of established runway information for $\{f_1, f_2, \dots f_{i-1}\}$ as well as all arrivals, thus

$$\bar{\mathcal{C}}_f(\lambda_f) = \left(\sum_{f' \in F^{Arr}, \bar{\lambda}_{f'} = \lambda_f} \chi_{W_s}(\mathrm{STA}_{f'}) + \sum_{j<i,\ \lambda_{f_j} = \lambda_f} \chi_{W_s}\left(\mathrm{STD}_{f_j}\right) + 1 \right)^n \tag{5.22}$$

where W_s is such that $\mathrm{STD}_f \in W_s$. The summation in the above equation represents the number of flights (including arrivals) who share the same time window as f, that have already been assigned to λ_f. This lexicographic optimisation procedure is summarised in Algorithm 2.

Algorithm 2 (Lexicographic runway assignment)

Input
1. Set of departures $\{f_i, i = 1, \dots, |F^{Dep}|\}$ in ascending order of STD;
2. The apron information for each departing flight;
3. For each $i = 1, \dots, |F^{Dep}|$, the set of admissible runways Λ_f;

Initialize $i = 1$

Step 1 Find time window W_s such that $\mathrm{STD}_{f_i} \in W_s$;

Step 2 Solve the sub-problem (5.20)-(5.22) to assign runway λ_{f_i} to f_i;

Step 3 If $i = |F^{Dep}|$, the algorithm terminates; otherwise, $i = i + 1$, go to **Step 1**

Output Runway assigned to each departing flight

5.6.3. Iterative Apron and Runway Assignment Procedure

Since the apron assignment procedure (Algorithm 1) and runway assignment procedure (Algorithm 2) rely on fixed runway and apron information, respectively, the two submodules need to alternate until no further changes are made to apron and runway information after a full cycle of the two procedures. This is summarised as Algorithm 3.

Algorithm 3 (Iterative apron-runway assignment)

Input
1. Set of flights $\{\mathcal{F}_i, i = 1, \dots, M\}$ in descending order of priority;
2. Set of departures $\{f_i, i = 1, \dots, |F^{Dep}|\}$ in ascending order of STD;
3. The apron and runway information of each flight in the current operation;
4. For each $i = 1, \dots, M$, the set of aprons Ω_i^{BA} adjacent to the corresponding terminal where the airline is based;
5. For each $i = 1, \dots, |F^{Dep}|$, the set of admissible runways Λ_f;

Initialize	Let APR_0 and RWY_0 denote the apron and runway information in current operation. Set $k = 1$
Step 1	Perform Algorithm 1 with RWY_{k-1} as input to obtain apron assignment solution APR_k
Step 2	Perform Algorithm 2 with APR_k to obtain runway assignment solution RWY_k
Step 3	If $\mathrm{APR}_k = \mathrm{APR}_{k-1}$ and $\mathrm{RWY}_k = \mathrm{RWY}_{k-1}$, the algorithm terminates; otherwise, $k = k + 1$, go to **Step 1**
Output	Apron and runway assigned to each flight

Remark 2. *The convergence of Algorithm 3 requires that no apron or runway information of any flight is updated in a full iteration. The primary criterion of the proposed apron-runway assignment is distance minimisation, despite various features involving capacity constraints, a priori preferences, and nonlinear congestion. Therefore, Algorithm 3 is expected to converge within a few iterations as it is based on a fixed distance matrix with very limited options on the runway assignment branch. This is indeed confirmed by the numerical results in Figure 8.15.*

Remark 3. *For the proposed apron-runway assignment, the runway direction is required as input because it determines the entry and exit points of relevant flights. For strategic planning, two versions of the apron-runway assignment will be generated, one for each runway direction. For pre-tactical planning, depending on the expected/current wind direction, the corresponding assignment result can be generated. For simplicity, the change of runway direction within a day of operation is not considered.*

5.6.4. Determination of COBTs Within the A-CA Simulation

The proposed apron-runway assignment is mainly based on distance metrics and a number of physical and operational constraints and preferences. This procedure is designed for pre-tactical operations and does not rely on any particular surface network simulation models. However, in order to validate the new apron-runway assignment results and quantify their impact on airport operations, the A-CA simulation model will be invoked to generate various KPIs for comparison purposes.

To enable the ACA simulation, one prerequisite is the off-block times, which determine when the departures enter the surface network. Under the new apron-runway assignment, the taxiing times of these flights may be changed, and their off-block times should be updated accordingly to make sure that they reach the runway end within acceptable range from the CTOT (e.g. within $[-3, 2]$ minutes from the CTOT in the case of PEK).

The determination of off-block times requires an iterative procedure, which involves the ACA simulator for an accurate estimation of the taxi-out times, given that the off-block times of many flights may be altered simultaneously. The following algorithm computes the COBTs using CTOTs as fixed inputs. The target is that the simulated take-off times are within [-3, 2] minutes (min) slots from the given CTOTs. In view of the congestion effect and stochastic nature of the simulation, the termination criterion requires that more than 90% of the departures meet their slots. All the relevant times in Algorithm 4 are in minutes.

Algorithm 4 (Determination of COBTs within ACA simulation)

Input
1. The calculated take-off time CTOT_f of each departing flight $f \in F^{Dep}$;
2. TOBT_f of flight $f \in F^{Dep}$ in the current operation;
3. The apron and runway solution from Algorithm 3.

Initialize Let $X_0 = \{\mathrm{COBT}_f : f \in F^{Dep}\}$, $k = 1$

Step 1 Perform ACA simulation with the apron/runway assignment from Algorithm 3, based on the COBTs X_{k-1} to obtain the taxiing time TT_f for each $f \in F^{Dep}$

Step 2 Set the take-off times $\mathrm{TOT}_f = \mathrm{COBT}_f + \mathrm{TT}_f$ for $f \in F^{Dep}$.

If $\left|\{f \in F^{Dep} : \mathrm{TOT}_f - \mathrm{CTOT}_f \in [-3, 2]\}\right| \geq 0.9 \times |F^{Dep}|$,

terminate the algorithm; otherwise, go on to **Step 3**

Step 3 Set $\mathrm{COBT}_f = \mathrm{CTOT}_f - \mathrm{TT}_f$ for each $f \in F^{Dep}$ where $\mathrm{TOT}_f - \mathrm{CTOT}_f \notin [-3, 2]$, let $X_k = \{\mathrm{COBT}_f : f \in F^{Dep}\}$

Step 4 Set $k = k + 1$ and go to **Step 1**

Output COBTs of all departure flights

5.7. EXTERNAL ASSESSMENT AND DISCUSSION OF THE APRON-RUNWAY ASSIGNMENT PROCEDURES

The proposed apron-runway assignment procedure is characterised by the following features:

1. It is guided by the priorities of the flights, which are derived from the apron assignment rule and expert opinions;
2. Its solutions are primarily based on free-taxiing distances on the network, which does not consider taxiing dynamics or conflicts; and
3. It is constrained by a number of operational constraints concerning the connecting flights, dwell times, apron capacities, runway capacities, and airlines.

Although this optimisation procedure does not consider detailed taxiing dynamics, it works well on a pre-tactical level for O-D assignment for the following reasons:

- The objective of distance is directly related to taxiing time (without congestion) and fuel consumption. Moreover, minimising the taxiing distance could potentially reduce the possibility of conflicts as it eliminates long-range taxiing routes and the instances of runway incursion;
- The computational procedure is rather efficient, allowing fast prototyping and local refinements; and
- For now, the network distances are based on free-flow conditions. They can be easily replaced by taxiing times obtained from A-CA simulation, which yields more realistic optimisation results.

5.8. SUMMARY

This chapter has proposed a pre-tactical framework for assigning aprons and runways at busy airports. The key design philosophy is distance minimisation with established priorities of flights and preferences of aprons/runways. This leads to a priority-based lexicographic optimisation framework, which assigns flights in sequence while abiding by stand availability constraints and runway utilisation considerations. To accommodate possible deviations of actual in-block/off-block times (i.e. AIBT, AOBT) from their respective schedules, which should be taken into account in pre-tactical operations, a data-driven robust approach is adopted within the proposed apron-runway assignment framework. This work is different from existing ones on partial or integrated airport surface operation in that it is the first to optimise origin-destination configurations of taxiing traffic from a network optimisation perspective, while considering qualitative assignment preferences and quantitative capacity and network constraints.

A case study of PEK is carried out in Chapter 6, to quantitatively assess the benefits of the new apron-runway assignment, including taxiing distance reduction and increased gate assignments. The resulting apron-runway assignment need to be further integrated with dynamic routing and off-block control in a real-time decision environment, and evaluated using detailed airport surface simulations, to be completed in Chapter 8.

CHAPTER 6 CASE STUDY OF THE JOINT APRON-RUNWAY ASSIGNMENT IN PEK

6.1. SCOPE AND PURPOSE OF THE CASE STUDY

The main purpose of this case study is to assess the validity and effectiveness of the proposed apron-runway assignment presented in the previous chapter using real-world data. The scope of the validation includes the entire operation process in terms of inbound, turn-around, outbound, and take-off process, from the perspective of the aircraft-centric operation, that takes place on runways, taxiways, and aprons. The assumptions made in this chapter are identical to those mentioned in Section 5.1.

As this research focuses on enhancing airport surface operation by means of integrated and maximised utilisation of resources, other external factors such as active ATC intervention, ground handling delay, airport closure caused by severe weather, aircraft mechanical failure, are not within the purview of the numerical validation.

6.2. FLIGHT INFORMATION AND EXISTING APRON and RUNWAY ASSIGNMENT

6.2.1. Flight data

The data used in this study include empirical data from PEK between 26th March to 28th October in 2017 (Summer-Autumn Flight Season), consisting of a set of critical attributes of each flight (e.g. flight number, aircraft type, ETA/ATA, FR, ETD/ATD, gate usage, runway usage), operational rules and regulations and constraints (e.g., Aeronautical Information Publication (AIP), taxiing route, and taxiing constraints). Reference data for the base simulation should be sampled from a typical day of operation, which, according to

EUROCONTROL (2013), needs to satisfy the following: 1) one should use real traffic data representative of the actual operations to be simulated; 2) traffic demand should correspond to the nominal operation and traffic distribution, undisrupted by extreme or singular events (e.g. severe convective weather); and 3) the operational period in question should be determined in view of the objectives of the simulation.

In this case, the selected traffic demand (00:00-23:59 14th September 2017) is deemed to adequately represent the typical operation of PEK. Hourly movement on this day is shown in Figure 3.5. The whole day was chosen for the simulation (in the actual simulation, one-hour warm-up and cool-down sessions were included, leading to a 26-hour simulation period). Information for some representative flights at PEK is shown in Appendix 2. This dataset, along with operational rules, regulations, and constraints, as well as network supply are used to construct the baseline scenario, building on which the proposed design and optimisation are implemented and tested.

6.2.2. Apron operation

1）Rules and constraints

The airline distribution in the landside shown in Table 3.3 determines the apron location where the aircraft can be parked. In other words, the aircraft should be parked at the apron corresponding to its airline terminal if the aircraft is assigned to a bridge-stand, not only because passengers board via the bridge connecting the flight to the terminal, but also because a series of pre-flight (e.g. check-in, ticket, lounge) and after-flight activities (e.g. luggage claim) should be done in the corresponding terminal. Hence, before re-assigning the apron, rules such as airlines-terminal correspondence, apron size, apron equipment were followed. For remote stands, as passengers are transferred via shuttle bus services, it can be used for various types of flights as long as they satisfy the basic physical constraints (e.g. size, equipment). More apron/stand assignment constraints/rules and assignment priorities can be found in Section 5.4.

2) Apron sectorisation

Based on the current distribution of stands, the apron areas are sectorised into 27 disjoint aprons (see Figure 6.1) through a balanced consideration of spatial configuration, operational characteristics of aircraft flow, operational regulation, and aircraft parking type. The objective of the apron sectorisation is to facilitate the modelling of aircraft movement through the taxiway network while simplifying detailed movement within the apron areas. This research aggregates individual gates/stands into apron areas, with the following additional considerations:

- Gates/stands whose corresponding taxiing routes have significant overlap (or potential conflict) need to be clustered into the same apron area;
- Gates/stands whose corresponding taxiing routes are relatively independent (with few conflicts) should be clustered into two different apron areas; and
- Flows into/from any two different apron areas should be independent.

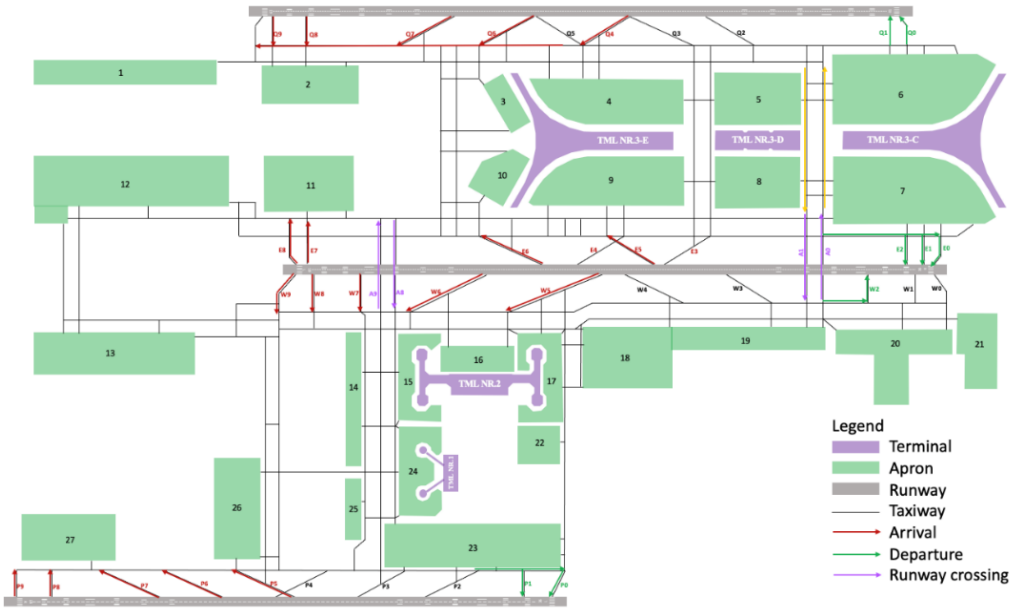

Figure 6.1. Airport surface network topology

3）Apron assignment preferences

Besides the operational rules and constraints of apron assignment at PEK, stand priority ranking agreed by stand assignment operator is also considered. Some base airlines with a large number of flights operating from/to PEK have their apron assignment priorities and preferences. Some examples are shown in Table 6.1, where the notation A>B means that A has a higher priority over B. Taking a flight from HU airline as an example, the stand operator first checks the usage of Apron NR.1 if there is an available stand, otherwise, sequentially check the usage of W2, W1, N1 until one becomes available. It is noted that the number of aprons (e.g. Nr.3, Nr.5) in Table 6.1 is the apron marking shown on the real-world apron surface, which are further sectorised and replaced by the new apron numbers shown in Figure 6.1 in the proposed research.

Table 6.1. Examples of apron assignment preference

Airlines	D/I[16]	Preferences Ranking
CA and its agencies	D	Nr.3 Bridge stand > Nr.3 Remote stand
CA	I	Nr.5 Bridge stand> Nr.5 Remote stand > Nr.4
HU and its agencies	D	NR.1 > W2 > W1 > N1
HU	I	NR.2 International Bridge-stand > W2 > W1
MU	I	NR.2 International Bridge-stand > Nr.2> NR.7> NR.8
MU and FM	D	NR.2 Domestic Bridge-stand >NR.8 > NR.7 > NR.6
CZ	I	T2 International Bridge-stand > Nr.2> NR.7> NR.8
CZ and its agencies	D	Connecting flights: NR.2 bridge-stand > NR.8 > NR.7 > NR.6 Single arrival: NR.2 bridge-stand> NR.7 >NR.6

[16] D and I respectively stand for domestic and international flights.

4) Minimum turn-around time

On the airside, besides the take-off, landing and taxiing processes, the turn-around phase is quite unique as a series of ground handling services need to be done (De Neufville et al., 2013). These include embanking, fuelling, de-fuelling, cleaning, baggage, and cargo services. Hence, the Minimum Turn-around Time (MTAT) is determined based on the aircraft type and airport logistics, which is a criterion in airport quality assessment. In PEK, according to the operational rule proposed by CAAC, the MTAT for different aircraft types is shown in Table 6.2. This has been applied to the proposed model.

Table 6.2. MTAT for different aircraft type in PEK

Number of seats	Examples of aircraft types	Minimum required time
≤ 60	E145, AT72, CRJ2	40
61-150	CRJ7, E190, A319	50
151-250	B757, B767, B787, A310, A320, A321	60
251-500	B747, B763, B777, A300, A330, A340, A350, MD11	75
≥ 500	A380	120

6.2.3. Runway Operation

This section introduces runway operational constraints and rules, and airline preferences, which are fully considered in the proposed model.

1）Runway entrance and exit points

Before taking off, each departure should be held at the designated runway threshold point until take-off clearance is issued by ATCOs. In PEK, except for some special aircraft types (i.e. B747-8, A380), each departure can choose to take off from the threshold points. On the other hand, for arrivals, the speed limit of the runway exit is 30kt, if the aircraft speed is below this speed limit, it can exit the runway from the nearest runway exit point. However, some super

heavy aircraft (B747-8, A380) has designated points for take-off or exit from the runway, and only designated runways that can be used.

The entrance and exit points of each runway at PEK are shown in Table 6.3, the corresponding locations of which can be found in Figure 6.1. For the middle runway 36R/18L, both sides (EAST and WEST) have independent exits. The use of either side is determined by the location of the assigned apron.

Table 6.3. Runway entrance and exit Points

Runway	Runway displaced threshold points	Runway Exit points
36L	P0, P1	P5, P6, P7, P8, P9
36R	E0, E1, E2, W1	**EAST**: E5, E6, E7, E8 **WEST**: W5, W6, W7, W8, W9
01	Q0, Q1	Q5, Q6, Q7, Q8, Q9
18R	P9, P8	Q0, Q1, Q2, Q3, Q4
18L	E8, E7, W7	**EAST**: E0, E1, E2, E3, E4 **WEST**: W0, W1, W2, W3, W4
19	U2, Q9, Q8	P0, P1, P2, P3, P4

2）Runway crossing points

When an aircraft taxiing from the east area to the west area, or vice versa, runway crossing is inevitable unless a long detour is considered. In general, there are two ways to cross the middle runway 36R/18L. The first one is to cross directly via four designated crossing points named A0, A1, A8, A9 (see Figure 6.1). Normally, A8 and A9 are mainly used in north operation, while A0 and A1 are mainly used in south operation. For example, if an aircraft crossing RWY 36R from west to east, it should wait at A9/A0 until clearance is issued.

Another way to cross the runway is via a ‘U shape’ located at the northernmost (the end of RWY36R), which is highlighted in red. Two routes named Route S6 and Route S7 are used

while crossing from east to west, and visa verse, respectively. Although long taxiing distance and time are expected, such a long detour do not add extra pressure to the middle runway, which may reduce conflicts and taxi delay caused by runway crossing, and increase runway utilisation during a peak hour.

3）Runway Assignment Rule

In Beijing TMA, designed Standard Instrument Departures (SIDs) and Standard Instrument Arrivals (STARs) are respectively used for guiding departures and arrivals to enter the airspace/approach. There are seven departure points (YV, CDY, TONIL, LADIX, RENOB, SOSDI and KM) and six entry points (KM, JB, BOBKA, VYK, DOGAR, GITUM) in the TMA. Figure 6.2 shows a schematic plot of positions of the departure fixes, where the three fixes to the west of the airport are associated with runways 36L and 36R, and the other four fixes are associated with runways 36R and 01. This configuration avoids route crossings in the TMA for departures.

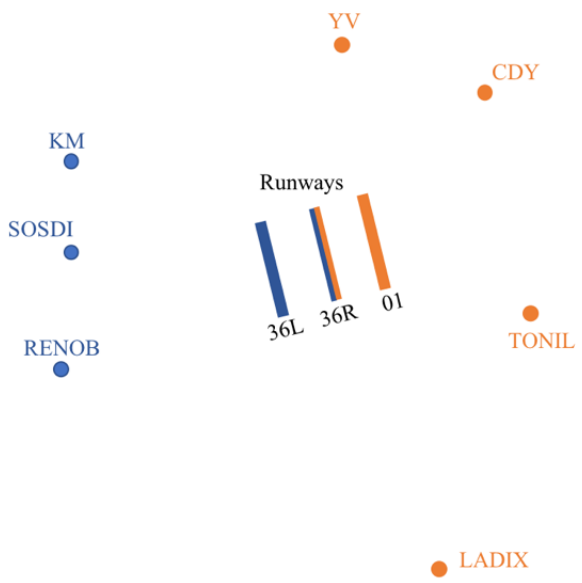

Figure 6.2. Relative positions of departure fixes (operation in north)

4）Airline preferences

Airlines have their own preferences for runway usage, which are summarised in Table 6.4, and derived from the interviews with SMEs (details of the interview can be found in Section 5.4.2).

All airlines listed in the table are base airlines, the sum of which accounts for more than half the movements at PEK. Their preferences are taken into account by SMEs while assigning runway and apron. Table 6.4 illustrates that the airlines prefer runways that are close to their designated terminals. The preferences are consistent with SMEs' assignment practice.

Table 6.4. Examples of runway preferences for some airlines

Airlines	Runway Preferences	Located Terminal	Terminal Area
CA	01/19 & 36R/18L	T3	EAST
CZ	36L/18R&36R/18L	T2	WEST
HU/JD	36L/18R & 36R/18L	T1&T2	WEST
MU	36L/18R &36R/18L	T2	WEST

6.2.4. Taxiway Operation

At PEK, each aircraft normally follows a standard taxiing route between each O-D pair, unless conflicts are envisaged in advance or the aircraft deviates from the assigned route. In this situation, the controller chooses alternative routes to resolve the conflict. The standard taxi routes are set up according to the Operational Manual of PEK, examples are illustrated in Figure 6.3. However, for extremely large aircraft, some taxiways are not allowed to be used due to the taxiway operational restriction (i.e. long wingspan).

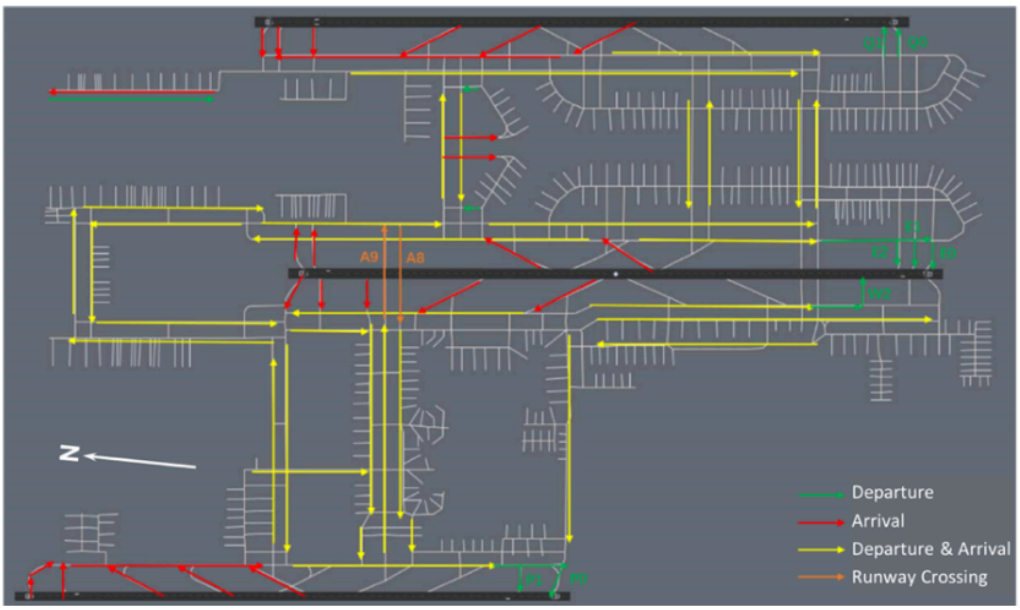

Figure 6.3. Single direction of taxi flow instruction in north direction (adopted from Operational Manual of PEK)

6.2.5. Operation of Special Aircraft Type

B747-8 and A380 are categorised as F-level aircraft, which are restricted due to their large size, long-distance acceleration/deceleration, and stand requirement. At PEK, this type of aircraft should follow exclusive operational regulation as follows.

- Three runways can be used for departure and arrival. However, RWY 01/19 and RWY 36R/18L have higher priority than RWY 36L/18R. RWY 36L/18R can only be used with the permission of ATC and AOCC;
- Some taxiways are not able to be used due to incompatible sizes; and
- Only designated stands, including three bridge-stands and eight remote stands can used for this special aircraft type.

The above special operational rules are fully incorporated in the proposed apron-runway assignment.

6.3. RESULTS OF THE PROPOSED JOINT APRON-RUNWAY ASSIGNMENT

The proposed apron-runway assignment framework is implemented and validated using the Beijing Capital Airport (IATA: PEK) as a case study. The airport surface is presented as a graph with 437 links and 313 nodes, and 83 origin-destination pairs. Figure 6.1 shows the topological layout of the PEK airport surface network, which contains three parallel runways and 27 apron areas (apron segregation refers to Section 0), 12 of which contain bridge stands that are directly connected to the terminals. All three runways operate under mixed modes (both departure and arrival).

The operational data on 14 September 2017 is used, which is a typical operational day with heavy traffic, to set up the ACA simulation and apron-runway assignment procedure. A total of 1757 flights were involved in this 24-hr period, whose characteristics are illustrated in Figure 6.4, along with the number of stands in each apron area. The runways were under mixed mode and were operating in north direction, with being designated 01, 36R and 36L.

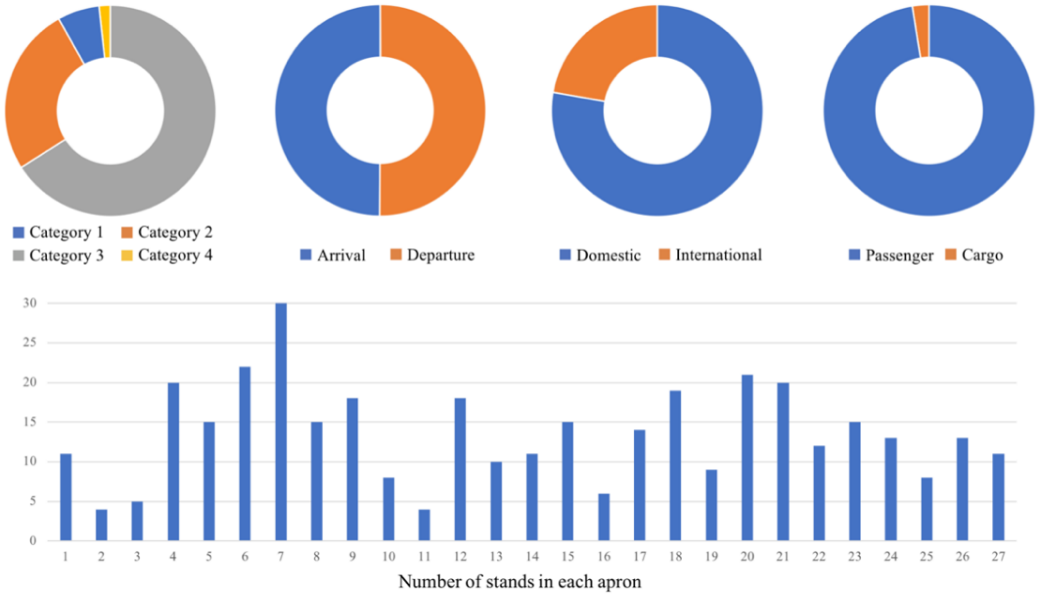

Figure 6.4. Flight characteristics (top) and number of stands in each apron (bottom)

This section starts by illustrating the apron-runway assignment results by setting the buffers $\delta_1^{Arr} = \delta_2^{Dep} = 0$, which means that no reservation is made to accommodate uncertain air traffic demands at PEK. The apron-runway assignment results are illustrated in Figure 6.5, and compared with the current apron-runway assignment (14 September 2017). In this figure, O-D distribution is demonstrated by showing, for each runway, the apron distribution of flights that use that runway (either for departure or arrival). By comparing the current with the proposed apron-runway assignment, it can be observed that: (1) the flights are spatially distributed closer to their designated runways in the new design, due to distance minimisation used as the primary objective of the algorithms; (2) ungate assignments (i.e. usage of remote stands) have decreased significantly compared to the old design, as bridge stands receive higher priorities in the apron assignment rules.

In Figure 6.6, the O-D assignment results with zero buffers $\delta_1^{Arr} = \delta_2^{Dep} = 0$ and with buffers $\delta_1^{Arr} = -20, \delta_2^{Dep} = 40$ is compared. It can be seen that as the level of conservatism increases (i.e. larger buffers), stand utilisation decreases due to the larger dwell intervals shown in (5.16), leading to more remote stand allocations. By comparing the left and right columns of Figure 6.6, shows that despite the slight increase in remote stand assignment, the two solutions show overall similar O-D distributions.

To further quantify the impact of different levels of conservatism in the robust apron-runway assignment, the total taxiing distances and percentages of gate assignments with different levels of buffers is summarised in Table 6.5. The results are based on 10 independent runs of the apron-runway assignment algorithm, each with randomized intra-cluster ranking. As expected, as the buffers increase, the number of gate assignments reduces as stand utilisation becomes lower. On the other hand, the total taxiing distance slightly decreases as well, due to the fact that some flights are assigned to remote stands that are closer to the runways, as can be seen from Table 6.8.

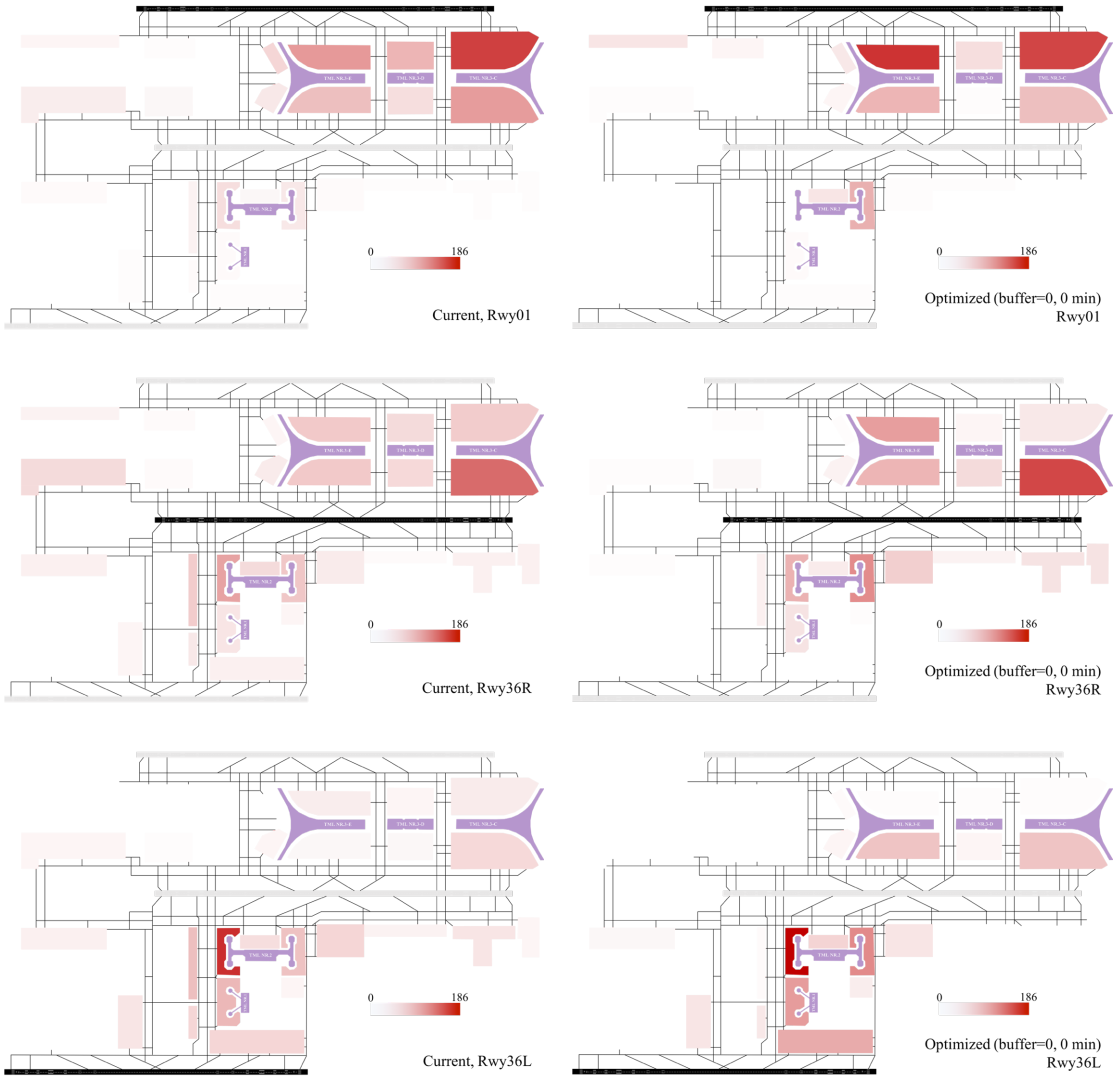

Figure 6.5. O-D distribution before (left column) and after (right column) apron-runway assignment ($\boldsymbol{\delta_1^{Arr} = \delta_2^{Dep} = 0}$). Each row shows the number of flights in each apron that uses Runway01 (top), Runway36R (middle) and Runway36L (bottom), respectively.

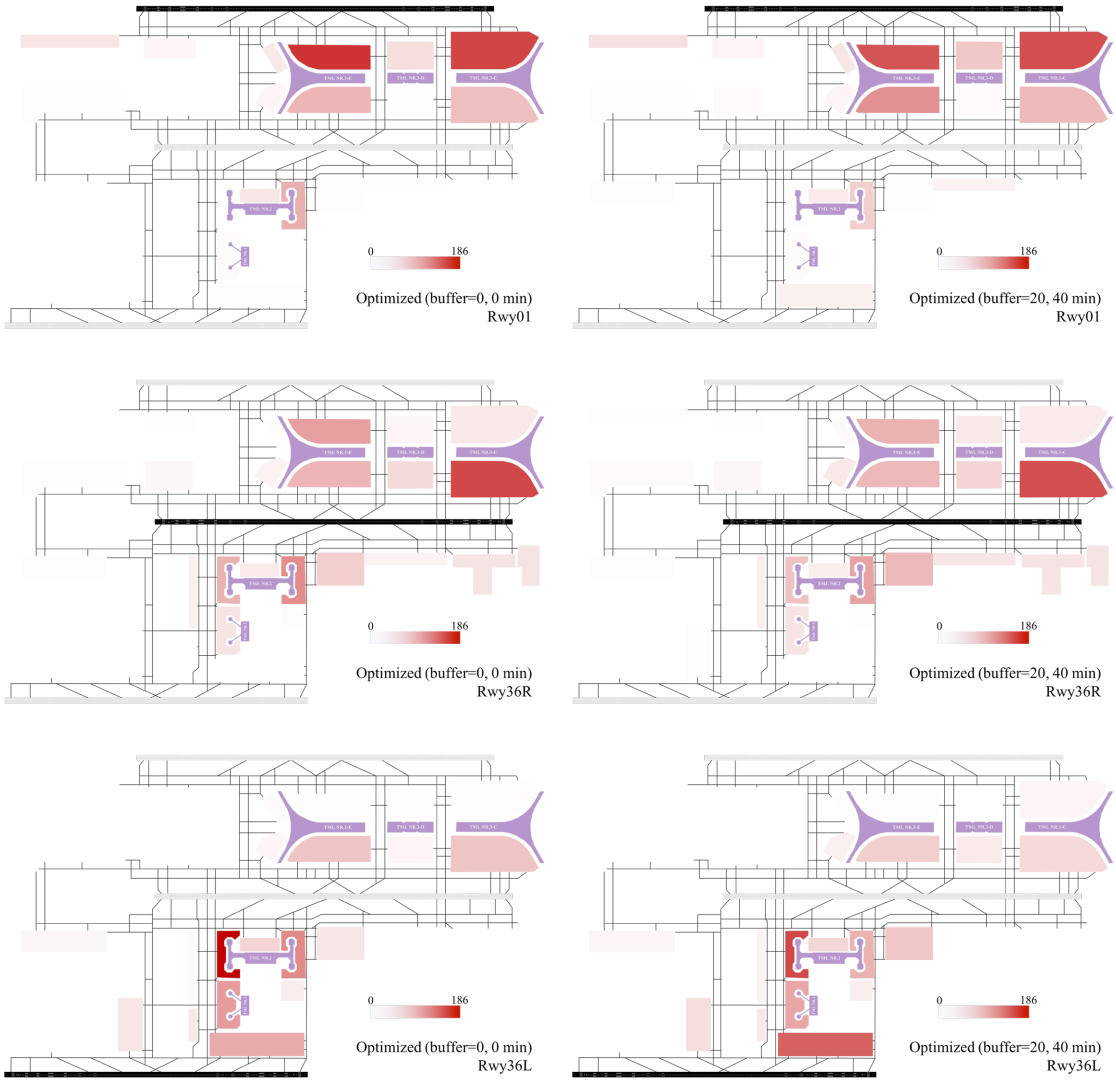

Figure 6.6. O-D distribution results of the proposed apron-runway assignment, left column: $\boldsymbol{\delta_1^{Arr} = 0, \delta_2^{Dep} = 0}$; right column: $\boldsymbol{\delta_1^{Arr} = -20, \delta_2^{Dep} = 40}$. Each row shows the number of flights in each apron that uses Runway01 (top), Runway36R (middle) and Runway36L (bottom), respectively.

Table 6.5. Comparison of apron-runway assignment results with different buffers

Buffer (min) $\delta_1^{Arr}, \delta_2^{Dep}$	Total taxiing distance (km)	Gate assignment (%)
$0, 0$	4303	84.5
$-5, 10$	4291	82.0
$-10, 20$	4260	79.6
$-15, 30$	4254	77.8
$-20, 40$	4250	76.0
$-25, 50$	4242	73.9

Furthermore, the taxiing distance reduction compared to the current operation by different flight attributes is checked and summarised in Table 6.6, with $\delta_1^{Arr} = -20, \delta_2^{Dep} = 40$ buffers as an input, and the off-block times have been calculated in Algorithm 4. With the exception of super-heavy aircraft (-2.1%), all other flight types receive distance reduction by double digits. Note that the airport has very limited stands of category 1 (accommodating aircraft with super-heavy category), which means that there is little room for manoeuvre when it comes to apron and runway assignment for super heavy aircraft, and the longer taxiing distance in the new design is caused by a different runway assignment solution.

Table 6.6. Taxiing distance reduction (compared to the current operation) by different fight attributes. The buffers are $\delta_1^{Arr} = -20, \delta_2^{Dep} = 40$

	All flights	Category			Flight type		Oper. type	
		SH	H	M/L	Dom	Int	Arr	Dep
Taxiing distance reduction (%)	15.5	-2.1	19.3	15.7	16.4	12.7	11.8	20.4

6.4. SUMMARY

This chapter has introduced a case study of the IARA in PEK, by first providing the scope and the purpose of the proposed research, following by flight data and operational-related information. Based on the operational constraints, rules, and preferences of runways, taxiways, and aprons, as well as empirical data collected form PEK, the proposed apron-runway assignment optimisation scheme that encompasses lexicographic and iterative approaches proposed in Chapter 5 is assessed. Moreover, different buffers are considered in the O-D distribution, in order to further quantify the impact of different levels of conservatism in robust O-D assignment. Lastly, taxiing distance with different flight categories has been checked.

Building on the results of the IARA, Chapter 7 develops Dynamic Route Search (DRS) and Integrated Dynamic Routing and Off-block (IDRO) optimisation algorithms in a real-time decision environment, with empirical data and operational rules as inputs.

CHAPTER 7 DYNAMIC ROUTE SEARCH AND OFF-BLOCK CONTROL

The dynamic search for taxiing path is performed in a real-time fashion, by considering path impedance that involves taxiing distance, number of curves, and number of aircraft sharing segments of the path. In particular, when a departing aircraft is pulled from the stand or an arriving aircraft exits the runway, it is dynamically assigned an optimal path by an algorithm, which takes it to the least-impeded route for taxiing to its destination. This algorithm needs to account for possible conflicts between the aircraft in question and other aircraft whose existing taxiing route overlaps with the route to be determined.

The off-block control aims to find the optimal time for the departing aircraft to enter the network such that the total efficiency of the taxiing system can be improved, especially when combined with the DRS algorithm. The overall goal of the IDRO optimisation is to reduce taxiing time and possibility of conflict, and to increase runway utilisation.

7.1. DEFINITION AND CALCULATION OF DYNAMIC ROUTE IMPEDANCE

The route impedance is a dynamic variable which describes, for a given aircraft that follows such a route, the overall cost that it might experience. The route impedance consists of two components that respectively represent free-flow taxiing time and possible congestion from interacting with other aircraft on the surface network. In analogy to the impedance function from road traffic theory (BPR, 1964), it is expressed as

$$c_i(p;t) = t_p^0 \left(1 + \alpha \sum_j \sigma_{ij}(t) \right)^{\beta} \tag{7. 1}$$

where $c_i(p;t)$ denotes the (dynamic) impedance of route p for aircraft i at its origin with departure time t, t_p^0 denotes the free-flow time along route p, $\sigma_{ij}(t)$ represents possible interaction or conflict between aircraft i and j. The positive parameters α, β adjust the weight of congestion and nonlinearity of the impedance function, respectively. Obviously, in the summation above, only aircraft j whose current route overlaps with p is considered.

7.1.1. Free-flow Route Travel Time

Given an admissible route p with origin r and destination s, the set of nodes along the path is denoted $P = \{n_1, n_2, \dots, n_p\}$, where $P^c = \{n_{i_1}, n_{i_2}, \dots, n_{i_m}\} \subset P$ denotes the set of turning curves along this route. A turning curve is a node along a given route where the immediate upstream and downstream links are not geometrically aligned, so that a taxiing aircraft, even in the free-flow condition, needs to slow down before turning.

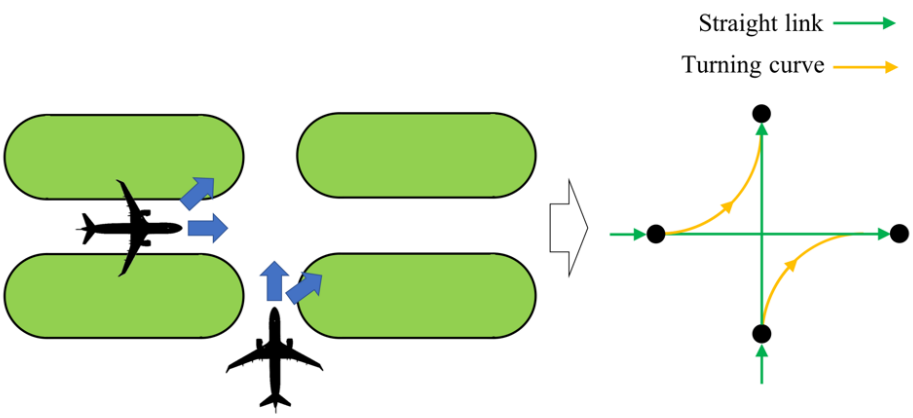

Figure 7.1. Network representation of turning curves

Figure 7.1 illustrates a typical taxiing intersection where only two straight movement and two turning movement are permitted. For simplicity, acceleration and deceleration are not considered when it comes to impedance calculations, and assume constant taxiing speeds along straight links (e.g. 10m/s) or turning curves (e.g. 5m/s). Using such a network representation, it is straightforward to calculate the free-flow times of all routes. It is also suitable for dynamic route search using dynamic programming (e.g. Dijkstra's algorithm).

7.1.2. Interaction Indicator σ_{ij}

In the definition of route impedance (7. 1), $\sigma_{ij}(t)$ needs to take into account two aspects of the conflict: (1) when i and j arrives at the overlapping segment of their respective routes at similar times, the conflict becomes significant and σ_{ij} is large; (2) $\sigma_{ij}(t)$ should be monotonic with respect to the length of the overlapping segment. In view of this consideration, the expression of σ_{ij} is devised as

$$\sigma_{ij}(t) = \frac{L_{ij}}{1 + \gamma\left\|\tau_i(t) - \tau_j(t)\right\|^2} \tag{7. 2}$$

For aircraft i and j, $\mathfrak{R}^{ij} = \{v_1, v_2, \dots, v_n\}$ is defined to be the overlapping segment of their respective routes, where each v_i represents a node. L_{ij} denotes the length of the overlapping segment. Given the current locations of aircraft i and j at time t, the vectors $\tau_i(t), \tau_j(t) \in \mathbb{R}^n$ represent the estimated times of arriving at each node in $\mathfrak{R}^{ij}$. The positive parameter γ adjusts the sensitivity of the interaction variable $\sigma_{ij}(t)$ to the squared difference of node arrival times $\left\|\tau_i(t) - \tau_j(t)\right\|^2$.

The key step in the calculation of the interaction indicator (7.2) is estimating the vector of node arrival times τ_i and τ_j. While such times can be easily retrieved if such times are in the past, they can be difficult to predict for interactions to take place in the near future. One way is to employ a model-predictive approach where a surface movement simulator is used to predict the arrival times at each node (see Figure 7.2, dashed arrow). However, this means the routing decision is dependent on a particular simulator, which not only renders the outcome less reliable, but also increases the computational burden in a real-time decision environment. Instead, this thesis adopts a simple approach by estimating $\tau_i(t), \tau_j(t)$ under the free-flow conditions following Section 7.1.1. In other words, the arrival times at each node in the near future is estimated using the free-flow times. More elaborated discussion of the interaction indicator σ_{ij} is provided in Section 7.4.1.

7.2. REAL-TIME DYNAMIC ROUTE SEARCH

It is noted that the impedance defined above is dynamically changing, as aircraft keep entering and leaving the surface network. It is also noted that the route decision of a particular aircraft would interact with those decisions of all relevant aircraft, making the route search problems coupled together through the definition of impedance. The solution algorithm for this type of problem can either follow a First-Come-First-Served (FCFS) approach or based on a rolling-horizon mechanism wherein only a small number of coupled route search problems need to be solved at a time. This chapter will explore both approaches.

7.2.1. FCFS Approach for Dynamic Route Search

In this section, a straightforward FCFS approach is adopted for dynamic route search based on the concept of dynamic route impedance. Namely, the routes of the flights are optimised in sequence, in the same order when they enter the taxiway network. This optimisation principle is natural to follow in a real-time operational environment, as the routes of relevant flights are only calculated when they enter the network, either through the runway exit ramp for arrivals, or apron exit for departures.

The FCFS dynamic route search procedure is illustrated in Figure 7.2.

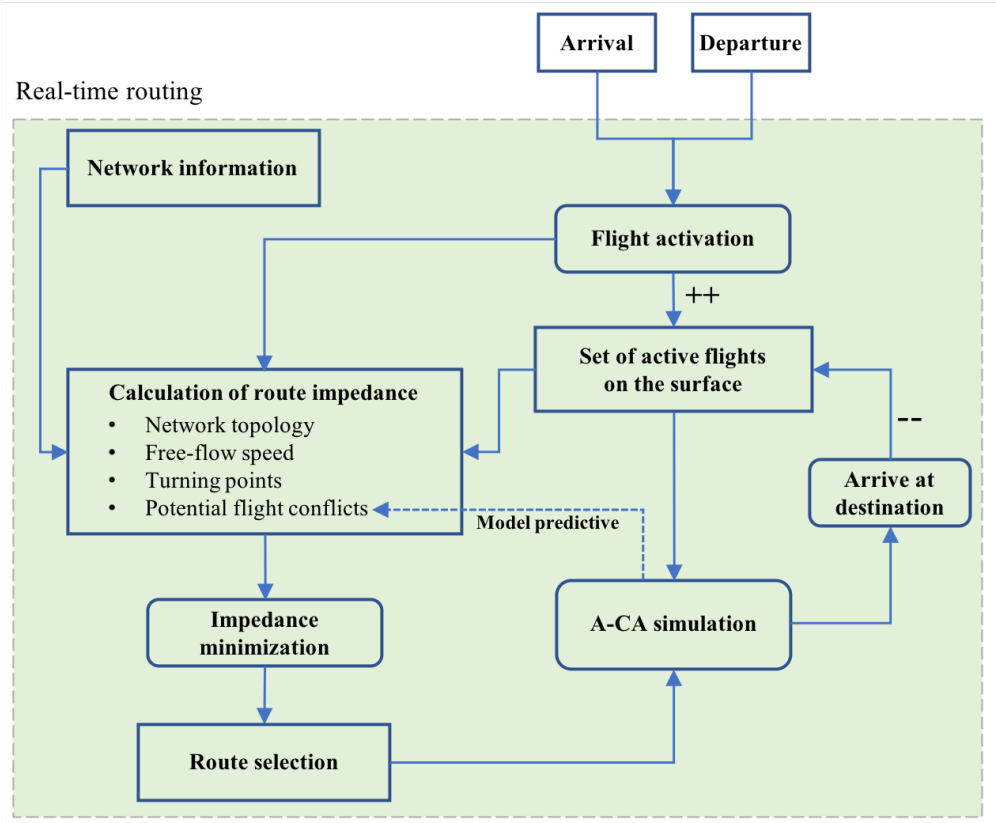

Figure 7.2. Flow chart of the FCFS dynamic route search procedure

The following algorithm summarises this approach.

Algorithm 5 (FCFS approach for dynamic route search)

Input

1. Set of flights $\{\mathcal{F}_i, i = 1, \dots, M\}$ in ascending order of their activation times, AT_i[17];
2. The O-D information for each flight;
3. Set of admissible routes P_i for each flight $\mathcal{F}_i$, according to the taxiing rules of the airport;

[17] For arrivals (or departures), their activation time is the time when they enter the taxiway network, i.e. through runway exit (or apron exit).

Initialize $t = 1$

Step 1 Determine the state set $S(t) = \{(p_i, x_i(t)): \mathcal{F}_i \in A\}$, where A denotes the set of active aircraft on the taxiway network, p_i is the route already assigned to $\mathcal{F}_i$, and $x_i(t)$ is the position of $\mathcal{F}_i$ along route p_i.

Step 2 If $t = AT_i$ for some flight $\mathcal{F}_i$, then calculate the impedance of all admissible routes in the set P_i based on the state set $S(t)$, and select the route with the least impedance to be assigned to $\mathcal{F}_i$. Otherwise, set $t = t + 1$ and go to **Step 1**.

Step 3 Load $\mathcal{F}_i$ into the surface network, set $\mathcal{F}_i$ to be active. Let $t = t + 1$ and go to **Step 1**.

7.2.2. Rolling Horizon Approach for Dynamic Route Search

The FCFS approach is easy to implement, especially in a real-time operational environment. However, strictly following a first-come-first-served principle, it may lead to sub-optimal solutions for route assignment. Hence, this section proposes a rolling horizon approach. Within each horizon, the routes assigned to a group of aircraft are optimised using a heuristic method. The operational period is divided into small horizons (e.g. 15min in length) $h_k, k = 1 \dots, K$. The rolling horizon approach is illustrated in Figure 7.3 and summarised in Algorithm 6.

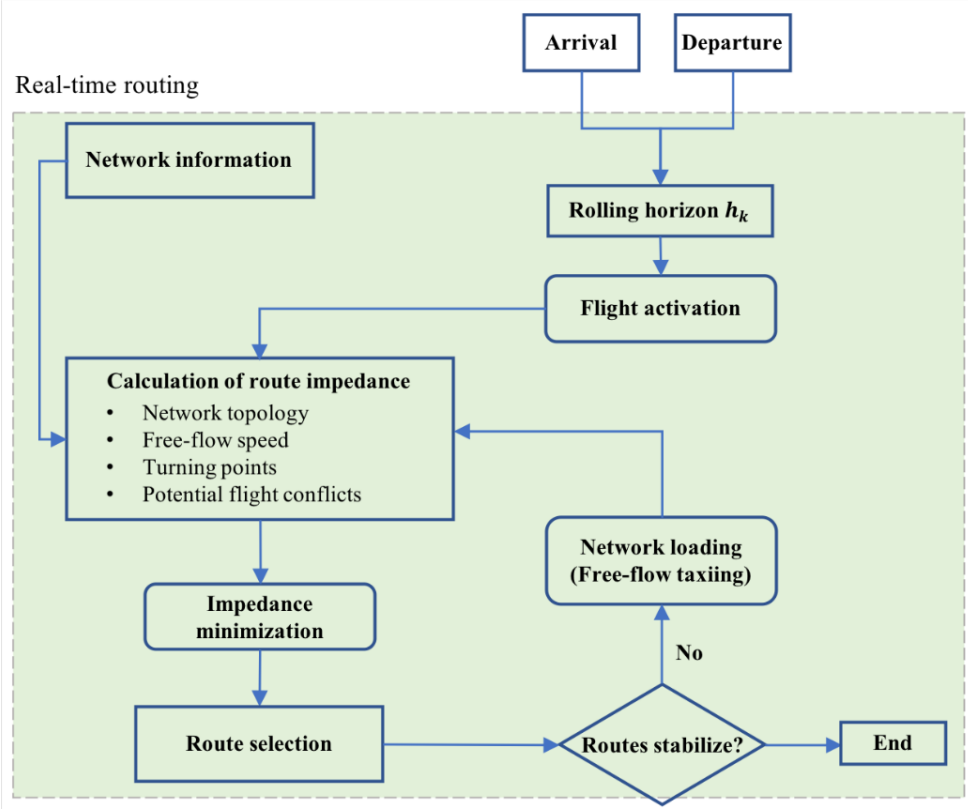

Figure 7.3. Flow chart of the rolling-horizon dynamic route search procedure

Algorithm 6 (Rolling horizon approach for dynamic route search)

Input
1. Set of flights $\{\mathcal{F}_i, i = 1, \dots, M\}$ in ascending order of their expected activation times, AT_i;
2. The O-D information for each flight;
3. Set of admissible routes P_i for each flight $\mathcal{F}_i$, according to the taxiing rules of the airport;

Initialize $k = 1$

Step 1 Form the subset of flights $\left\{\mathcal{F}_{i_j}, j = 1, \dots, m\right\}$ whose expected activation times $AT_{i_j} \in h_k$.

Step 2 Perform Algorithm 5 (FCFS approach for dynamic route search) on $\left\{\mathcal{F}_{i_j}, j = 1, \dots, m\right\}$, with the modification that each activated aircraft is loaded into the network under the free-flow conditions. That is, the state sets $\{S(t), t \in h_k\}$ are determined assuming that all the taxiing aircraft move along their designated routes with free-flow speeds.

Step 3 For $j = 1{:}\,m$

Re-assign to aircraft $\mathcal{F}_{i_j}$ the least-impeded route based on the state set $S(AT_{i_j})$.

End

Update the state sets $\{S(t), t \in h_k\}$ using the re-assigned routes.

Step 4 If the route of any aircraft is changed during Step 3, then repeat Step 3. Otherwise, go to Step 5.

Step 5 If $k = K$, then terminate the algorithm; otherwise, set $k = k + 1$ and go to Step 1.

In analogy to road traffic network modelling, Algorithm 6 is essentially an iterative loading procedure, where the free-flow assumption corresponds to an all-or-nothing assignment principle. The heuristic method may be able to converge and yield global-optimal solutions if the number of flights involved $\left\{\mathcal{F}_{i_j}, j = 1, \dots, m\right\}$ is small. However, optimising routes within a small group of flights at a time does not promise good performance results for the entire fleet. Therefore, one should carefully choose the horizons h_k to balance optimality and convergence of the algorithm.

7.3. INTEGRATED DYNAMIC ROUTING AND OFF-BLOCK CONTROL

The off-block control is performed for departure flights, where the actual off-block time (AOBT) ranges within the interval $[\mathrm{STD} - \delta_1, \mathrm{STD} + \delta_2]$, where STD is the scheduled time of departure, and δ_1, δ_2 are early and late departure buffers, respectively. For a given aircraft $\mathcal{F}_i$ with a designated route p, when time $t = \mathrm{STD}_i - \delta_1$, the off-block optimisation procedure is activated, which amounts to solving the following problem

$$\min_{\tau \in [\mathrm{STD}_i - \delta_1, \mathrm{STD}_i + \delta_2]} c_i(p; \tau + \mathrm{AD}_i) \tag{7.1}$$

where $c_i(p; \tau + \mathrm{AD}_i)$ is the impedance along route p at departure time $\tau + \mathrm{AD}_i$. AD_i denotes apron delay (apron holding time), which represents the duration between the off-block operation and when the aircraft leaves the apron and enters the taxiway network (see Section 5.6.4). The optimisation problem (7.1) can be solved by directly discretising the interval $[\mathrm{STD}_i - \delta_1, \mathrm{STD}_i + \delta_2]$, where the prediction of route impedance $c_i(p;\ \tau + \mathrm{AD}_i)$ for the near future is done by assuming free-flow conditions for all relevant aircraft on the surface network.

The integrated dynamic routing and off-block control (IDRO) is expressed as:

$$\min_{\substack{\tau \in [\mathrm{STD}_i - \delta_1, \mathrm{STD}_i + \delta_2] \\ p \in P_i}} c_i(p; \tau + AD_i) \tag{7.2}$$

7.3.1. FCFS Approach for IDRO

Algorithm 7 details a first-come-first-served approach for IDRO optimisation, where departing aircraft with earlier STDs receive IDRO optimisation before those with later STDs.

Algorithm 7 (FCFS approach for IDRO)

Input
1. Set of departing flights $\{\mathcal{F}_i, i = 1, \dots, M\}$ in ascending order of their scheduled time of departures, STD_i;
2. The O-D information of each departing flight $\mathcal{F}_i$;
3. Set of admissible routes P_i for $\mathcal{F}_i$, according to the taxiing rules of the airport;

Initialize $t = 1$

Step 1 Determine the state set $S(t) = \{(p_i, x_i(t)) : \mathcal{F}_i \in A\}$, where A denotes the set of active aircraft on the taxiway network, p_i is the route already assigned to $\mathcal{F}_i$, and $x_i(t)$ is the position of $\mathcal{F}_i$ along route p_i.

Step 2 If $t = \mathrm{STD}_i - \delta_1$ for some flight $\mathcal{F}_i$, then determine the off-block time and route by solving the optimisation problem (7.2). Otherwise, set $t = t + 1$ and go to **Step 1**.

Step 3 Load $\mathcal{F}_i$ into the surface network, set $\mathcal{F}_i$ to be active. Let $t = t + 1$ and go to **Step 1**.

7.3.2. Rolling Horizon Approach for IDRO

Similar to Section 7.2.2, the operational period is divided into small horizons (e.g. 15min in length) $h_k, k = 1 \dots, K$. The rolling horizon approach for IDRO is summarised in Algorithm 8.

Algorithm 8 (Rolling horizon approach for IDRO)

Input
1. Set of departing flights $\{\mathcal{F}_i, i = 1, \dots, M\}$ in ascending order of their scheduled time of departures, STD_i;
2. The O-D information of each departing flight $\mathcal{F}_i$;

3. Set of admissible routes P_i for $\mathcal{F}_i$, according to the taxiing rules of the airport;

Initialize $k = 1$

Step 1 Form the subset of flights $\{\mathcal{F}_{i_j}, j = 1, \dots, m\}$ that satisfy $[\mathrm{STD}_{i_j} - \delta_1, \mathrm{STD}_{i_j} + \delta_2] \subset h_k$.

Step 2 Perform Algorithm 7 (FCFS approach IDRO) on $\{\mathcal{F}_{i_j}, j = 1, \dots, m\}$, with the modification that each activated aircraft is loaded into the network under the free-flow conditions. That is, the state sets $\{S(t), t \in h_k\}$ are determined assuming that all the taxiing aircraft move along their designated routes with free-flow speeds.

Step 3 For $j = 1{:}\,m$

For aircraft $\mathcal{F}_{i_j}$, solve the problem (7.2) based on the state sets $\{S(t), t \in [\mathrm{STD}_{i_j} - \delta_1, \mathrm{STD}_{i_j} + \delta_2]\}$, and re-assign the off-block time and route accordingly.

End

Update the state sets $\{S(t), t \in h_k\}$ using the re-assigned off-block times and routes for all flights $\mathcal{F}_{i_j}, j = 1, \dots, m$.

Step 4 If the off-block time or route of any aircraft is changed during Step 3, then repeat Step 3. Otherwise, go to Step 5.

Step 5 If $k = K$, then terminate the algorithm; otherwise, set $k = k + 1$ and go to Step 1.

7.4. PRELIMINARY ASSESSMENT AND DISCUSSION OF THE ROUTING STRATEGIES

7.4.1. Examples And Discussion of the Interaction Indicator

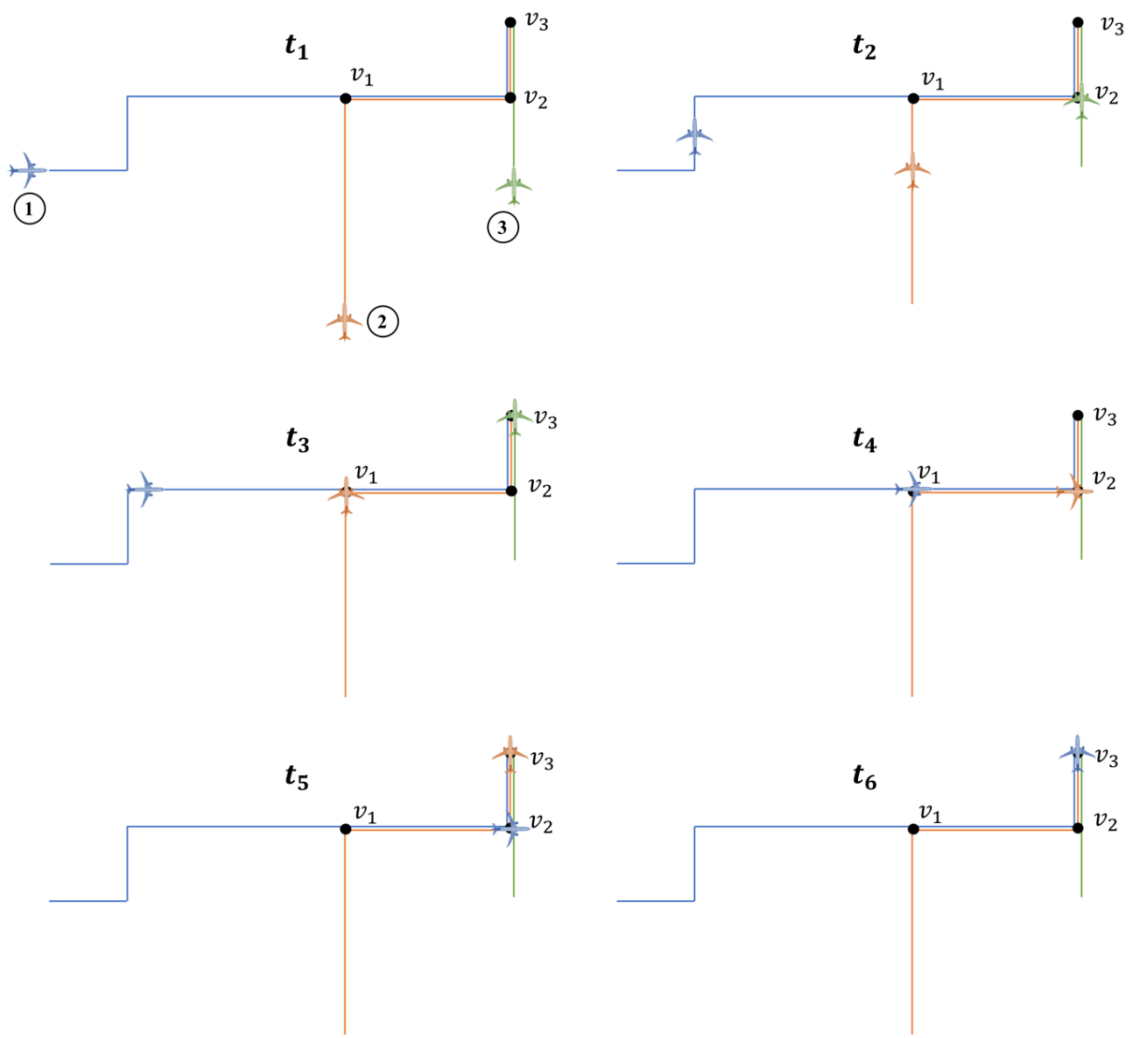

Figure 7.4. Node arrival times, $t_1 < t_2 < t_3 < t_4 < t_5 < t_6$.

This is shown how to use node arrival times to quantify the potential conflicts among taxiing aircraft. In Figure 7.4, three aircraft 1-3 with partially overlapping routes are considered. Taking

flights 1 and 2 for instance. The set of overlapping nodes $\Re^{12} = \{v_1, v_2, v_3\}$. By definition, they are

$$\tau_1(t_1) = (t_4, t_5, t_6), \tau_2(t_1) = (t_3, t_4, t_5)$$

Then, their interaction indicator is computed as

$$\sigma_{12}(t_1) = \frac{L_{v_1 \to v_2} + L_{v_2 \to v_3}}{1 + \gamma((t_4 - t_3)^2 + (t_5 - t_4)^2 + (t_6 - t_5)^2)}$$

where $L_{v \to w}$ represents the length of link starting and ending with v and w, respectively. Similarly, the other interaction indicators are:

$$\sigma_{13}(t_1) = \frac{L_{v_2 \to v_3}}{1 + \gamma((t_5 - t_2)^2 + (t_6 - t_3)^2)}$$

$$\sigma_{23}(t_1) = \frac{L_{v_2 \to v_3}}{1 + \gamma((t_4 - t_2)^2 + (t_5 - t_3)^2)}$$

Clearly, it is $\sigma_{23}(t_1) > \sigma_{13}(t_1)$, as flight 3 is more likely to have conflict with flight 2 than flight 1. Moreover, assuming that $t_1 = 0, t_2 = 1, t_3 = 2, t_4 = 3, t_5 = 4, t_6 = 5$,

$$\sigma_{12}(t_1) = \frac{L_{v_1 \to v_2} + L_{v_2 \to v_3}}{1 + 3\gamma}, \qquad \sigma_{13}(t_1) = \frac{L_{v_2 \to v_3}}{1 + 18\gamma}$$

which leads to $\sigma_{12}(t_1) > \sigma_{13}(t_1)$. This means that flight 1 is more likely to interact with flight 2 than with flight 3. This makes sense as the flight 3 is much further ahead compared to flight 1 along its path. Also it is calculated:

$$\sigma_{23}(t_1) = \frac{L_{v_2 \to v_3}}{1 + 8\gamma} < \sigma_{12}(t_1)$$

which means flight 2 is more likely to have conflict with flight 1 than with flight 3.

Remark. In the expression of the interaction indicator $\sigma_{ij}(t)$, if γ is very small, then σ_{ij} is mainly related to the length of the overlapping segment of the respective routes. On the other hand, if γ is large, then σ_{ij} is much more prone to the temporal overlap of their trajectories.

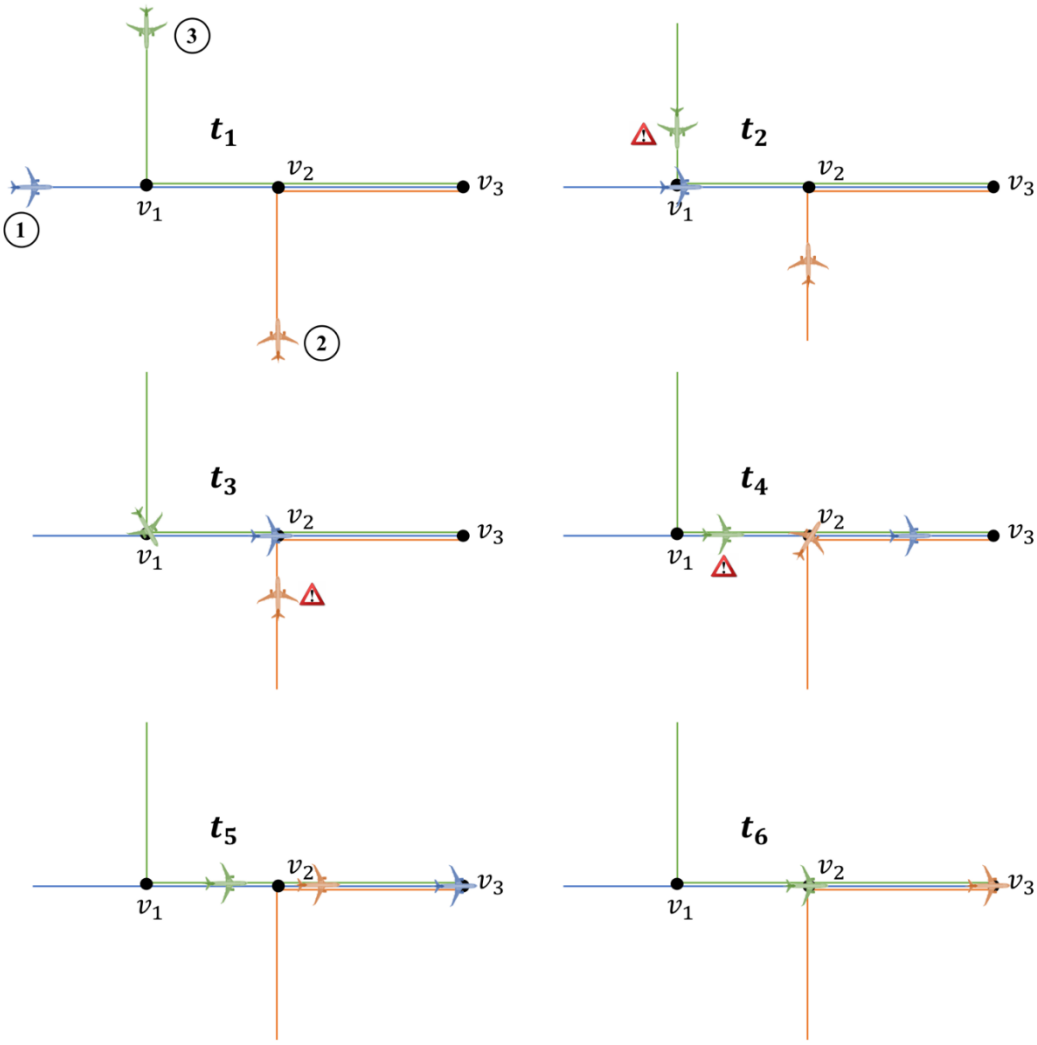

Figure 7.5. Node arrival times, $\boldsymbol{t_1 < t_2 < t_3 < t_4 < t_5 < t_6}$.

Another example is illustrated in Figure 7.5, which involves more conflicts than the previous one, indicated using the warning sign next to the relevant aircraft. The interaction indicators are calculated as:

$$\sigma_{12}(t_1) = \frac{L_{v_2 \to v_3}}{1 + \gamma((t_4 - t_3)^2 + (t_6 - t_5)^2)}$$

$$\sigma_{13}(t_1) = \frac{L_{v_1 \to v_2} + L_{v_2 \to v_3}}{1 + \gamma((t_2 - t_3)^2 + (t_6 - t_3)^2 + (t_7 - t_5)^2)}$$

In this case, the situation is a bit more complicated. If let $t_1 = 0, t_2 = 1, t_3 = 2, t_4 = 3, t_5 = 4, t_6 = 5$, then,

$$\sigma_{12}(t_1) = \frac{L_{v_2 \to v_3}}{1 + 2\gamma}, \qquad \sigma_{13}(t_1) = \frac{L_{v_1 \to v_2} + L_{v_2 \to v_3}}{1 + 14\gamma}$$

Then, the relationship between σ_{12} and σ_{13} is dependent on the choice of γ.

7.4.2. Examples And Discussion of the Dynamic Route Impedance.

The dynamic route impedance using an example is illustrated in Figure 7.6. The target aircraft (black, indicated using 't' in subsequent notations) is located on the left, whose destination is the runway end, with two potential routes (highlighted in green in Figure 7.6). The first route (on the left panel) involves two potential interactions, σ_{t2} and σ_{t1}, both are significant as the approximate node arrival times are similar. In the case of the second route (on the right panel), there is only one significant interaction indicator, σ_{t1}. Therefore, under appropriate choices of parameters, the second route may have a smaller impedance despite the fact that it has a larger free-flow time (two more turning curves than the first route).

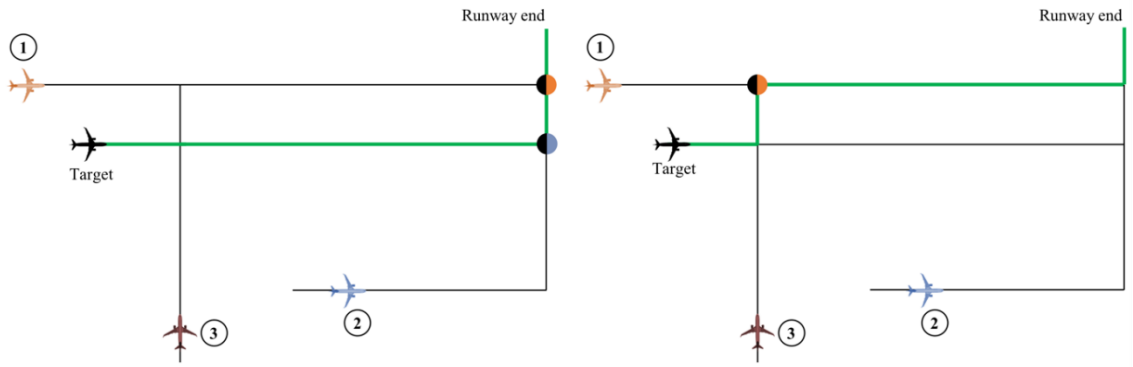

Figure 7.6. Example of the dynamic route impedance.

To illustrate the dynamic nature of the proposed route impedance, a similar scenario is considered as in Figure 7.7, but with a slightly later start time for the target flight, which is shown in Figure 7.7. In this case, the interaction indicator σ_{t3} has become significant for both the first and second routes, and no other significant interaction indicators are found. Therefore, in this case, the first route is preferred as it has a smaller free-flow time.

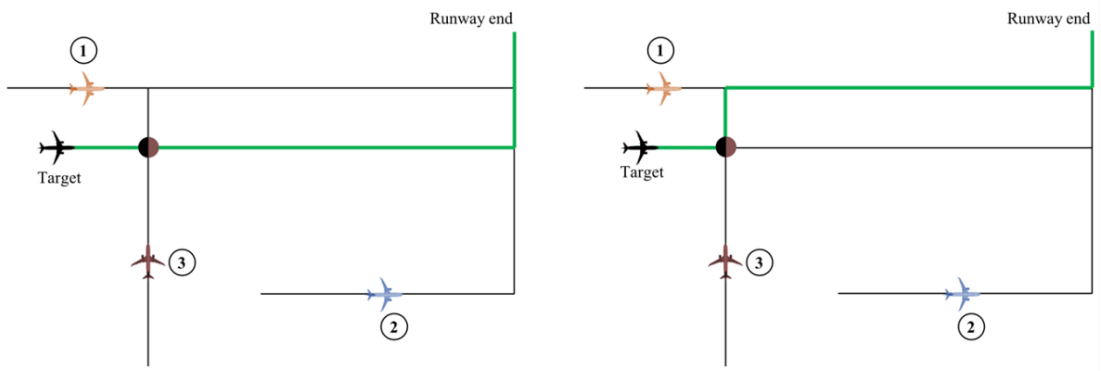

Figure 7.7. Example of the dynamic route impedance (with a later start time).

7.4.3. FCFS vs Rolling Horizon

In the previous sections, two optimisation approaches are proposed for both routing and joint off-block and routing, namely, the FCFS strategy and a rolling horizon strategy. Their pros and cons are discussed and compared here.

The FCFS strategy determines relevant control parameters (off-block time, or route assignment) at the exact time when the relevant aircraft enters the network. Such a decision is made based solely on the current status of the surface network given by existing taxiing aircraft. Such a decision does not take into account the possibility that the route impedance, on which the off-block time or route are based, for an earlier aircraft might be affected by some other aircraft that enters the network at a later time, as illustrated in Figure 7.7. This means that the routing decision for an aircraft is made in isolation, without collaborative decision making among a group of flights. This is the main challenge that the rolling horizon approach aims to address.

On the other hand, the rolling-horizon approach takes into account the joint impact of the routing decisions of a group of flights on each other, as indicated by the iterative loading and assignment procedure in Algorithms 6 and 8. If and when the algorithms converge, the decision for each aircraft has fully incorporated those for other aircraft in the same horizon. However, the rolling horizon approach has two potential issues. (1) when the horizon is large or the number of aircraft involved is significant, the algorithms may not converge. In this case, a relaxed termination criterion, either with regard to the oscillation or the decrease of the total impedance, should be imposed. (2) the rolling horizon approach relies on the free-flow assumption to simplify the calculation, but this may lead to unreliable estimates especially if the number of flights is large or the buffer window $[\mathrm{STD} - \delta_1, \mathrm{STD} + \delta_2]$ is large.

Therefore, in practice, one should carefully consider the choice of optimisation strategies, in conjunction with the complexity of the surface movement, and the decision space considered for the operation.

7.5. SUMMARY

This chapter has performed the dynamic search for taxiing path in a real-time fashion. The path impedance is first determined by considering taxiing distance, number of curves, and number of aircraft sharing segments of the path. Based on the definition of path impedance, two optimisation approaches are proposed for both routing and joint off-block and routing, namely, the first-come-first-served strategy and a rolling horizon strategy. The overall goal of the IDRO optimisation is to reduce taxiing time and possibility of conflict, and to increase runway utilisation. This is done by dynamically assigned an optimal path by an algorithm, which takes the aircraft to the least-impeded route for taxiing to its destination while subjects to their assigned time slots, when a departing aircraft is pulled from the stand, or an arrival aircraft leaves the runway. Lastly, pros and cons of the two optimisation solutions also have been discussed and compared.

Based on the proposed integrated framework, Chapter 8 performs a comprehensive validation process, which is undertaken both qualitatively and quantitatively, to validate the veracity of the proposed model, the effectiveness of the proposed methodology, as well as provide potential implementation and application suggestions in the future.

CHAPTER 8 VALIDATION OF THE INTEGRATED RUNWAY-TAXIWAY-APRON OPERATIONS

This chapter presents validation results for the proposed integrated runway-taxiway-apron operations, by first introducing the key performance indicators (KPIs) used for assessing surface network operations, and then the cellular automata simulation model, followed by extensive test results that evaluate the effectiveness of the optimisation algorithms at different operational levels. Furthermore, a series of quantitative validation is checked by SMEs, together with the quantitative assessment, to validate the feasibility of the proposed concept, the veracity of the proposed model, as well as the effectiveness of the proposed methodology.

8.1. VALIDATION OF THE INTEGRATED AND JOINT SURFACE OPERATION

8.1.1. Purpose of Validation

Validation is a process of confirmation by providing objective evidence demonstrating the requirements for a certain intended usage or application have been fulfilled. Following the directions given by EUROCONTROL for TMA validation (EUROCONTROL, 2013a), both qualitative and quantitative validation techniques are adopted to achieve the following objectives of the airport surface operation:

- To demonstrate the operational validity of the proposed integrated and joint of runway-taxiway-apron optimisation design;
- To assess if the proposed method fulfils the originally designed objectives;
- To identify the potential weaknesses of the method and develop mitigation measures; and
- To assess the safety-related work of the proposed method.

8.1.2. Means of validation

Following the instructions of EUROCONTROL for TMA design validation, and to assess the validity and effectiveness of the proposed research, a combination of quantitative and qualitative assessment of the results based on the PEK case study is performed. The *qualitative assessment* refers to the sound operational judgement of the proposed design by providing evidence of its operational feasibility for the proposed design, as well as potential application and implementation in airports in the future. Qualitative assessment is typically undertaken by SMEs and can be based on the results of the proposed models.

On the other hand, *quantitative validation*, involves "quantified" results produced in the form of numerical data, normally relying on tools that provide numerical proof, e.g., computer-based simulation. This number validation is of importance as the interview opinions collected from SMEs may be biased by the opinion of the highest in the hierarchy. Therefore, to make the results both reliable and integral, quantitative validation with comparison KPIs and the qualitative assessment by SMEs are adopted to validate the proposed work. Figure 8.1 illustrates the flow chart of the validation process.

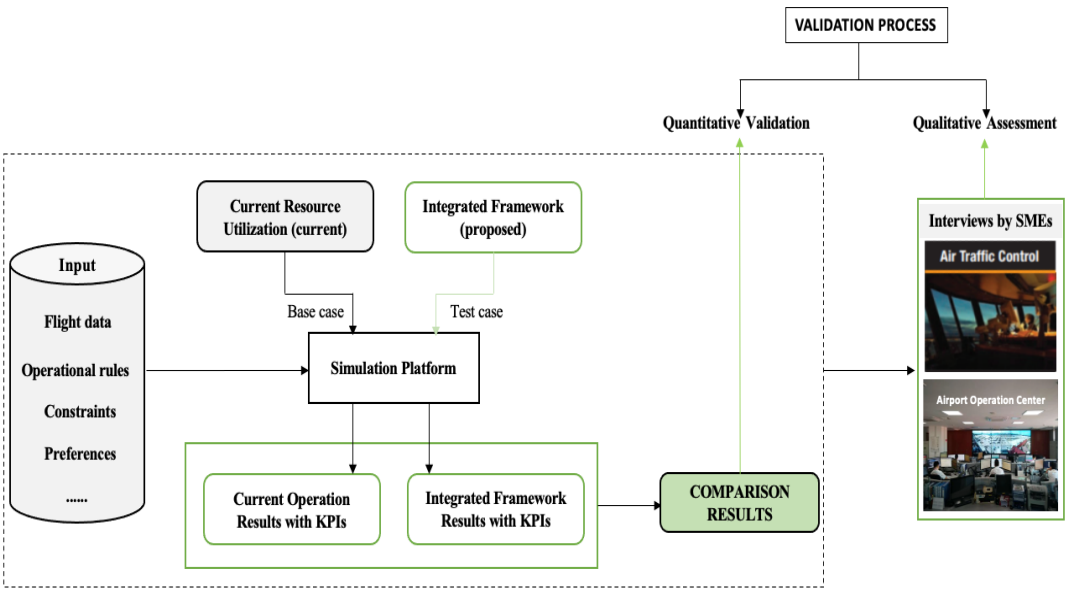

Figure 8.1. Flow Chart of the validation process

8.1.3. Qualitative Assessment of Simulation Results and Implementation Suggestions

The third round of qualitative assessment was conducted to validate the effectiveness of the proposed integrated model and to provide suggestions for potential applications and implementation in the future. This was completed from three aspects by means of *interviews with SMEs and representatives of various stakeholders* via online meetings.

The first aspect was the validation of the simulation set up for the Base Case and the Test Case models. This was achieved by reviewing the detailed setup in simulation (see Sections 8.3.1 & 0 & 8.3.3) and the results of the calibration (see Section 8.3.6) as well as the simulation output in terms of conflict distributions (Figure 8.33) and the distribution of stand utilisation (Figure 6.5). An airside resource manager (an SME from PEK) justified the model set-up in terms of key input parameters (e.g., probabilities for each runway exit for different aircraft types, runway threshold usage, runway occupancy time, runway crossing time, speed ranges, taxiway intersection rules), simplifications, and assumptions, as well as confirming that the conflict hotspots and resource utilisation simulated by A-CA were generally consistent with those of the real world. Moreover, the dynamic runway throughput curves and route sets were also checked by the manager (see Section 7.2).

The second aspect is the validation of the proposed optimisation framework at different operational levels. For this, the SMEs checked the comparative results of the Base Case and the Test Case of the A-CA models (see Sections 8.4 & 8.5 & 8.6), leading them to confirm that the proposed methodology indeed holds promise for improving the operational efficiency of the airport surface. In addition, given that the required information and communication technologies are in place, the proposed optimisation framework may be adopted gradually at certain airports.

The third aspect is to gain insights into the operational feasibility of the proposed integrated optimisation, and its potential for field implementation in the future. For this purpose, a series of semi-structured interviews was arranged with representatives of different stakeholders.

The criteria for the questionnaire design were the same as for the previous one (see Section 5.4.2). In this section, the questionnaire was used to understand the Communication Navigation Surveillance (CNS) capabilities in Chinese airports, because it is fundamental to the implementation of the proposed framework. In addition, the questionnaire attempted to obtain opinions and advice from various perspectives of aircraft operation. The criteria for the selection of the stakeholders focused on their working experience in large airports or airlines, and the variability of their perspectives. To meet these criteria, five representatives of different stakeholders associated with ATCO, Airport operators, Airline, and CAAC were interviewed, including four interviewees with an average of 7 years of work experience, and a senior pilot with 15 years of flying experience. These included an ATCO from Ningbo ATC station, a stand operator from Hangzhou Xiaoshan airport, a flight dispatcher from Hainan Airlines, an engineer in charge of flow management from CAAC, and a senior pilot from Air China Airlines.

As the individual responses from the interviewees are varied, their answers are processed and summarised below.

Question 1: Is there any surveillance equipment to follow each status of the aircraft moving on the airport surface?

Answer 1: Either airfield surveillance or ADS-B [18]is used in China's airports. For some of large and hub airports, such as Guangzhou Baiyun International Airport (IATA: CAN), Beijing Capital International Airport (IATA: PEK), airfield surveillance radars are used to monitor the status of the airfield operation and track the status of the aircraft moving on the surface. On the other hand, for other airports, due to the equipment cost or geographical structure restriction, ADS-B is used, such as, Ningbo Lishuo International airport (IATA: NGB), Xinjiang Diwopu International Airport (IATA: URC).

[18] ADS-B is the abbreviation of Automatic, Dependent, Surveillance, Broadcast, which is a kind of passive surveillance equipment that depends on GPS to navigate.

Question 2: What is the frequency of the surveillance equipment? What are the pros and cons of choosing ADS-B and Surveillance Radar?

Answer 2: The surveillance radar depends on that how many circles turn in a minute, e.g., if it takes 15 circles in a minute, the data is updated every four seconds. This figure also depends on the different suppliers and system setup at the airport. On the other hand, for the ADS-B, the data is updated every second.

Both ADS-B and Radar have pros and cons. The major difference between each is the cost of the equipment, as ADS-B is only one-ninth of the price of the Radar and with lower maintenance costs and long service life. However, as ADS-B is a passive surveillance equipment that is not able to verify the target location. Therefore, if the incorrect information was given by an aircraft, this error would not be identified. Furthermore, if the aircraft is not equipped onboard, this aircraft would not be shown on the ground surveillance terminal, while Radar is an active one.

Question 3: Which one is used in PEK to update frequency? Does it work from the perspective of the data transmission based on the current system equipment?

Answer 3: In PEK, surveillance radars are used, and the update frequency is 1 second. The data transmission completely meets the requirement of five seconds required in the proposed algorithm. However, if applying this methodology to other airports, it is important to be aware of the kind of the equipment used in advance and determining whether all the aircraft are equipped if ADS-B is used in the airport.

Question 4: Is there any method to transmit the dynamic path to the onboard device?

Answer 4: Currently, the technology is not available to provide taxiway navigational information to a pilot of an aircraft moving on the airport surface at PEK or other airports in China. Now, the aircraft is following by either the real-time order issued by the ATCOs or the "follow me" car to arrive its destination. If someday, the advanced CNS is able to support the datalink transmission along with advanced visual tools, such as Advanced-Visual docking

Guidance System (A-VDGS), which can display airport topology with specific name of each taxiway, and highlights the taxiways provided in a visual indication on a displayed map for pilots.

Question 5: Is it possible to implement dynamic route search on current airports in China?

Answer 5: ATCOs prefer to use standard taxiing routes, which may reduce excessive workload, and reduce the possibility of order mistakes. The workload for ATCOs and potential risks may offset the benefits of adapting a dynamic route. In addition, for some small airports (e.g., with one runway and several taxiways and aprons), alternative taxiing route options are limited. Furthermore, taxiway segment-based dynamic route search relies on, such as, advanced CNS technologies and taxi route decision tools, it is too hard to implement in the near future.

Question 6: Is it feasible for ATCOs to follow the dynamic taxiing route on the airport surface? What if an auto-system with real-time taxiing route guidance is provided?

Answer 6: Currently, aircraft are following by either the real-time order issued by the ATCOs or the "follow me" car to their destinations. Dynamic taxiing route may increase the ATCOs workload and order mistakes. Dynamic route search is to be achieved based on advanced technology and reliable assistant decision tools. For example, 1) a reliable assistant decision tool that can calculate an optimal taxi route for each aircraft; and 2) advanced CNS technology that can converts the resulting taxi route to a graphic (like a dynamic airport map) shown on the flight deck are required. In this case, pilot just follow the dynamic map to its destination.

It is noted that, the taxi route is not changed while assigned, unless there is an unpredictable conflicts or special situation that ATCOs would intervene. This is because providing an entire taxiing route before engine starting up that ATCOs have a foresight for potential conflicts. In addition, a dynamic segmented path search is not preferred currently, as it is crucial for ATCOs to prejudge conflicts from a holistic perspective.

In addition to the above Q&A, some stakeholders also have proposed the following questions after reviewing the proposed research. These questions are related to airport operation, some

of them are not considered in question, as they are beyond of this research scope, but they would be addressed in the future work.

Question 1: Is this research taking into account some special cases, such as runway switching, runway or apron closure?

Answer 1: The proposed methodology may apply to operation in each direction at PEK as well as other airports with priority-based operation. In this research, the framework is conducted in the north direction due to the strong prevailing direction at PEK (over 82% of the year). Similarly, the operation in the other direction may be modelled, by taking into account operational rules, constraints and preferences.

In addition, this model can solve some special cases as well, such as, some of aprons/runways temporally closed or unavailable. This can be achieved by adjusting parameters (e.g., adding or removing some aprons or runways) or operational rules (e.g. change runway configuration), constraints according to specific cases.

Question 2: Can this method be applied to a real-time operation?

Answer 2: Although this work is proposed on a pre-tactical level, the proposed methodology has considered the requirements of the real-time operation calculation. This real-time assignment may be achieved based on a rolling horizon algorithm (that dividing time period into small time window, e.g., one-hour or two-hour), using updating time as inputs (e.g., TOBT instead of STD). In this case, some uncertainty, such as the buffer time within the apron used in question, may be minimised. The resulting assignment, in terms of the number of gate assignments may be improved (as the number of gate assignment is highly related to the gate occupancy period for each flight).

Question 3: Has this research considered the aircraft de-icing process in winter? From the perspective of the airline, an aircraft prefers to be assigned to a bridge-stand, though a remote stand close to the de-icing apron is preference while de-icing procedure is needed.

Answer 3: Aircraft de-icing process is not considered in question, as this research focuses on maximising resource utilisation by integrated and joint optimisation of aprons, runways, and taxiways on the airport surface. Although de-icing procedure is inevitable sometimes in winter or in extremely cold weather, there is a lack of information and data related to de-icing procedure. In addition, this research focuses on providing a novel idea on operation improvements under normal circumstance, which may be applied to most of the time in the year at PEK (over eight months). However, it is possible to add multi-scenario cases (by taking into account, such as, de-icing and luggage claim procedures, shuttle bus dispatch) in the model, if necessary, in future work.

8.2. Definition and Measuring Key Performance Indicators

Key Performance Indicator (KPI) a numerical tool for measuring current, past, or expected future performances, as well as actual progress in achieving performance objectives. The definition of the KPIs should be based on the intention of the performance objectives, which must support objectives (ICAO, 2005a).

This section introduces the following KPIs, which are widely adopted to assess performance in airport surface operations, which should also be used to validate the effectiveness of the proposed integrated optimisation research.

8.2.1. Taxi Time

Taxi time is one of the KPIs proposed by ICAO (2005a), used to evaluate the operational effectiveness on airport surface. Reduction of the taxi time is one of the objectives that has been adopted to achieve time efficiency on airport surface operation. The total taxi time is the sum of actual taxiing- in and -out time, which includes waiting time and conflict resolution time. Specifically, taxiing-in time is the time interval of an arriving aircraft from touch-down on the runway to wheel-on time at the stand, including the waiting time during the entire taxi-

in process, whereas taxiing-out time is the time interval of a departing aircraft from wheel-off at the stand to take-off from the runway, including the waiting time during the whole taxi-out process and lining up at the runway holding point for take-off.

From the perspective of operation, taxi time may be classified into actual and unimpeded taxi time. The unimpeded taxi time is defined as the time interval of an aircraft between origin and destination without the interference of other traffic. It is the lowest time period required to complete an operation in period of low traffic (PRC, 2012). Compared to an unimpeded taxi time, an additional waiting time in the taxi phase is included in actual taxi time, which may be due to capacity constraints (e.g. lining up and waiting for departure at the runway threshold), conflicts (e.g. head-on conflict at intersections, or pushback conflict at aprons), congestion (e.g. waiting at the apron taxiway for stand clearance).

The numerical difference between actual and unimpeded taxiing time may represent the operation effectiveness on airport surface. For small differences, the actual taxiing time is close to the unimpeded taxiing time, where the aircraft is moving in a good condition with less conflicts; for large differences, the movement condition may be congested with many conflicts.

8.2.2. Conflicts

Doc.9854 (ICAO, 2005a, p2-11) shows that '*the purpose of conflict management is to limit, to an acceptable level, the risk of collision between an aircraft and a hazard*'. Conflict occurs whenever there is a competing demand for a resource. It may occur at any places, such as, runways, taxiways, and aprons.

8.2.2.1. Apron conflicts

Besides the time conflict between two consecutive aircraft for a stand that would be solved by stand (re-)assignment, an example of conflicts at the apron normally occur on apron taxiways due to overlap routes in close time among two or more aircraft. This is either due to a lack of coordinated assignment of taxiway and apron, or the inherent apron topology. Figure 8.3

illustrates two kinds of special apron topologies; for the left one, if an aircraft park at Gate 320, it would push-back to J4 first, and taxi along J4 and J5 until reach the designated point, waiting the order to start-up the engine. During its taxiing period, other aircraft located in this U-shaped area should wait at their stands until the conflict is resolved. In addition, this special topology with low-speed and long-distance taxiing may add extra taxi time within the apron, which also make challenges for predicting taxi time in real-time operations.

Another kind of conflicts occurs in the apron is due to aircraft wingspan, where two or more aircraft taxi-in or pushback occur from adjacent gates in close time, for example, conflict occurs when an aircraft is taxiing in the gate, while another aircraft is pushing back from the adjacent gate, or both of two flights are taxiing (pushback) in (from) adjacent gates (Figure 8.3). To solve the conflict, other aircraft should be waiting at the stand (or designated apron taxiway point) until the conflict is resolved.

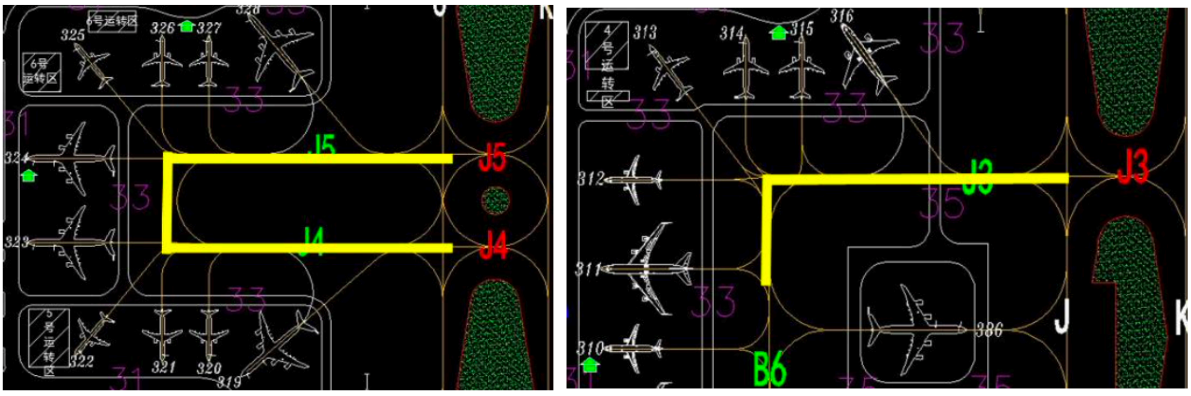

Figure 8.2. Examples of special apron structure (Yin, 2018)

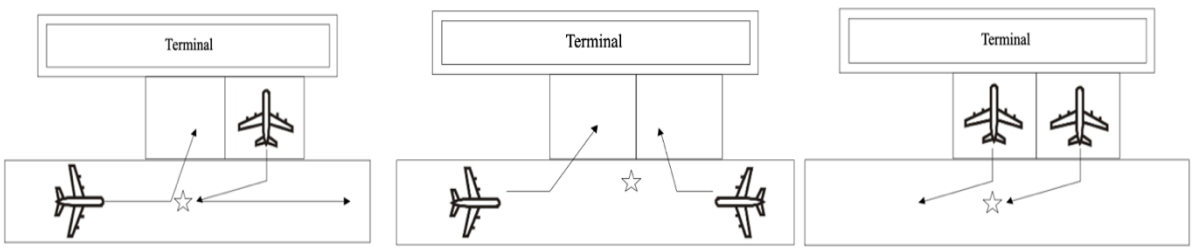

Figure 8.3. Examples of conflicts within aprons (Yin, 2018)

8.2.2.2. Taxiway Conflicts

Standard taxiing routes are commonly adopted in the most of airports, where the taxi route is fixed accordingly once O-D pair (apron-runway) is determined. Due to high flight demands on airport surface, many flights encounter conflicts with one another, particularly at nodes somewhere have two or more incoming links (diverse/merge taxiways). Figure 8.4 shows three common types of conflicts identified and considered on taxiways: crossing conflict, trailing conflict, and head-on conflict (Yin, 2015). Conflicts are detected or predicted when any two or more aircraft approaching the same node from different directions, such as, crossing conflict or head-on conflict. A tactical intervention is required to determine priority and resolve the conflicts and the priority is usually determined by controllers or autonomous decision system depending on operational rules or preferences, or other rules.

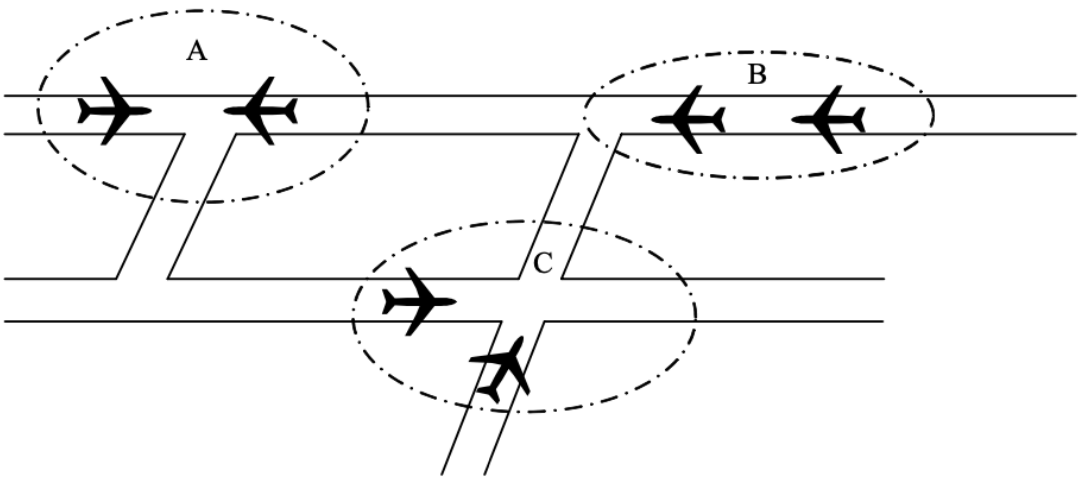

Figure 8.4. Examples of taxiway conflicts (Yin, 2015)

8.2.2.3. Runway conflicts

Runways are one of the scarcest resources on airport surface. Facing high flight demands, optimal runway sequencing has a positive impact on enhancing the runway use. However, in

some mega airport, runway crossing is inevitable, which is either due to the inherent surface topology or lack of coordinated assignment of runway and apron.

Three types of runway crossings tend to be found on airport surface, namely vertical runway crossing (Figure 8.5(a)), crossing via runway (Figure 8.5(b)) and runway end-slip crossing (Figure 8.5(c)), which are named based on their crossing places.

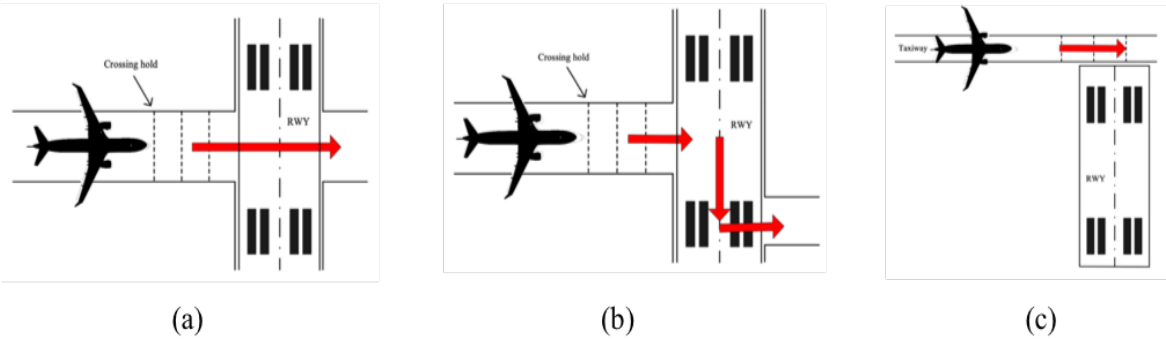

Figure 8.5. Examples of runway conflicts: (a)vertical runway crossing; (b)crossing via runway; (c) runway end-slip crossing (Yin, 2015)

Scenario A and C usually exist simultaneously in an airport. Because although directly crossing runway may reduce taxiing distance, it may put additional pressure on runway usage which may cause flight delay, in particular, in peak hours with high flight demands in terms of departures and arrivals. In this case, runway end-slip crossing is an alternative means of reducing waiting time for crossing the runway and mitigating runway delay due to runway crossing activity. Scenario B treats the part of runway as a taxiway, which would result in a reduction of runway use. This scenario is not common in real world, which may have been solved by building an additional by-pass taxiway.

8.2.3. Taxi Delay

Delay is defined as an event happening later than planned, scheduled, or expected. In aviation, flight delays are the result of conflicts, congestions, or upstream constraints. Delay is used or interpreted differently by various stakeholders (e.g. airlines, airports, ATC) or depending on one place (i.e. gate close delay, arrival delay, departure delay, taxi delay), which may be classified in two ways:

- Flight delays are measured as the actual time minus scheduled time. Similar definition refers to "*Delay is the difference between actual block time and ideal block time*" (ICAO, 2005a, p. B-2). For example, an arrival delay is calculated by actual time of arrival (ATA) minus scheduled time of arrival (STA), whereas departure delay is actual take-off time (ATOT) minus scheduled time of departure (STD).
- Whereas flight delays are also defined as the difference between actual travel time and nominal or unimpeded travel time. The numerical difference between actual taxi time and unimpeded taxi time is taxi delay, which may directly represent the operational efficiency on the airport surface. For example, large differences might be with many conflicts or congestion, while small differences mean moving in a comparable positive condition.

As this research focuses on the whole operation of airport surface, the first classification of the definition of taxi delay is used.

8.2.4. Runway Queuing and Throughput

Runway queuing is a phenomenon of many aircraft lining up and waiting at the runway or holding points for take-off. Queue length directly represents the current operation efficiency on airport surface, which depends on not only the runway throughput, but also the optimal coordination with other resources (e.g. the taxiway and the apron) on airport surface. Long runway queuing not only results in an extra runway waiting time that may cause other side

effects, such as, increased flight delays, fuel burn and emissions (waiting with engine-on), and congestions on runways or even "knock on" effects to the entire airport (e.g. a long queue may block the taxiway crossings connecting to the runway). Runway queuing should be controlled strictly to maintain surface operation. Meanwhile, reducing runway queueing is one of the most important objectives in airport surface operations. An optimal ground movement operation is to deliver the aircraft to the runway at the appropriate time (i.e. assigned runway time slot, or TTOT) to reduce engine-on waiting time at runway thresholds. This can be achieved by increasing runway throughput (optimal runway sequencing of departures and arrivals) or integrated operation with taxiway and apron (e.g. optimising gate release time and taxi route).

Runway throughput is defined as "*the number of aircraft that use the runway system per unit time, in a use pattern obeying the arrival-departure ratio and aircraft fleet mix*" (Barrer et al., 2005, p.2). This is related to the airport capacity that is defined as (ICAO (2005a), p. B-2) "*the maximum number of aircraft that can be accommodated in a given time period by the system or one of its throughput".* The capability of the runway throughput is constrained by a series of factors, including operational procedures (RWY allocation and taxi distance), runway configuration (number, alignment, and separation), runway availability (aircraft noise exposure, wind, visibility). The runway throughput may be increased by physical extension (e.g. build extra runway), changes in runway configuration (i.e. from segregated operation to mixed operation) or optimal runway utilisation. Physical extension includes building additional runways, or runway exits. However, this is in addition to expensive, time-consuming, and impractical to meet short-term goals, which may also increase the complexity of airport and airspace configurations and offset the capacity-related benefits of the investments. On the other hand, runway configuration is not easy to change as it is constrained by airspace configuration, CNS equipment, regulations, and so forth. Any change made should be strictly evaluated beforehand to keep operation safe and effective. In light of this, from the perspective of the flight operation, improving the runway utilisation is widely adopted in current operation and existing research. Runway sequence optimisation is one of the popular means of handling traffic demands (e.g., departures, arrivals, and coupled departure and arrival) at an airport in an

optimal sequence, taking into account airspace constraints, wake turbulence, aircraft capability and user preference. These methods have positive impacts on enhancing runway throughput and has been widely applied in most of airports. However, runway sequencing can not be achieved in isolation without considering the taxi process due to uncertainties. Any change made would result in an unachievable sequence as planned.

Following the aforementioned definition of KPIs, the effectiveness of the proposed research in quantitative validation process is performed through comparison of KPIs, which are widely obtained from the results of the base case (current operation) and the test case (proposed integrated optimisation operation) based on the A-CA model.

8.3. A-CA MODEL DEVELOPMENT FOR PEK AIRPORT

8.3.1. Airport Surface Network Modelling

In the A-CA model, the airport surface including the apron, the runway, and the taxiway, is modelled as a network, where the runway and the apron in question are considered as nodes. The specific movements within the apron and the runway are not considered in question as this proposed research is focusing on the O-D pair assignment. However, although the apron grouped all the stands in is modelled as a single node, the specific stand attributes, the number of stands, and aggregated taxiing time within the apron including taxi-in and taxi-out time, are modelled as the parameters and constraints in the proposed model. On the other hand, the runway occupied time for landing and take-off, and the take-off and landing separations, instead of the specific movement on the runway, are considered in the proposed model. In addition, considering each runway with different runway exits, the exit probabilities of each runway for different aircraft categories (SH, H, M, L) is also considered, the corresponding values are determined by the observation and ATCO survey. Figure 8.6 illustrates the flowchart

of the A-CA modelling. The apron and the runway modelling are introduced in Section 0 and 8.3.3, respectively.

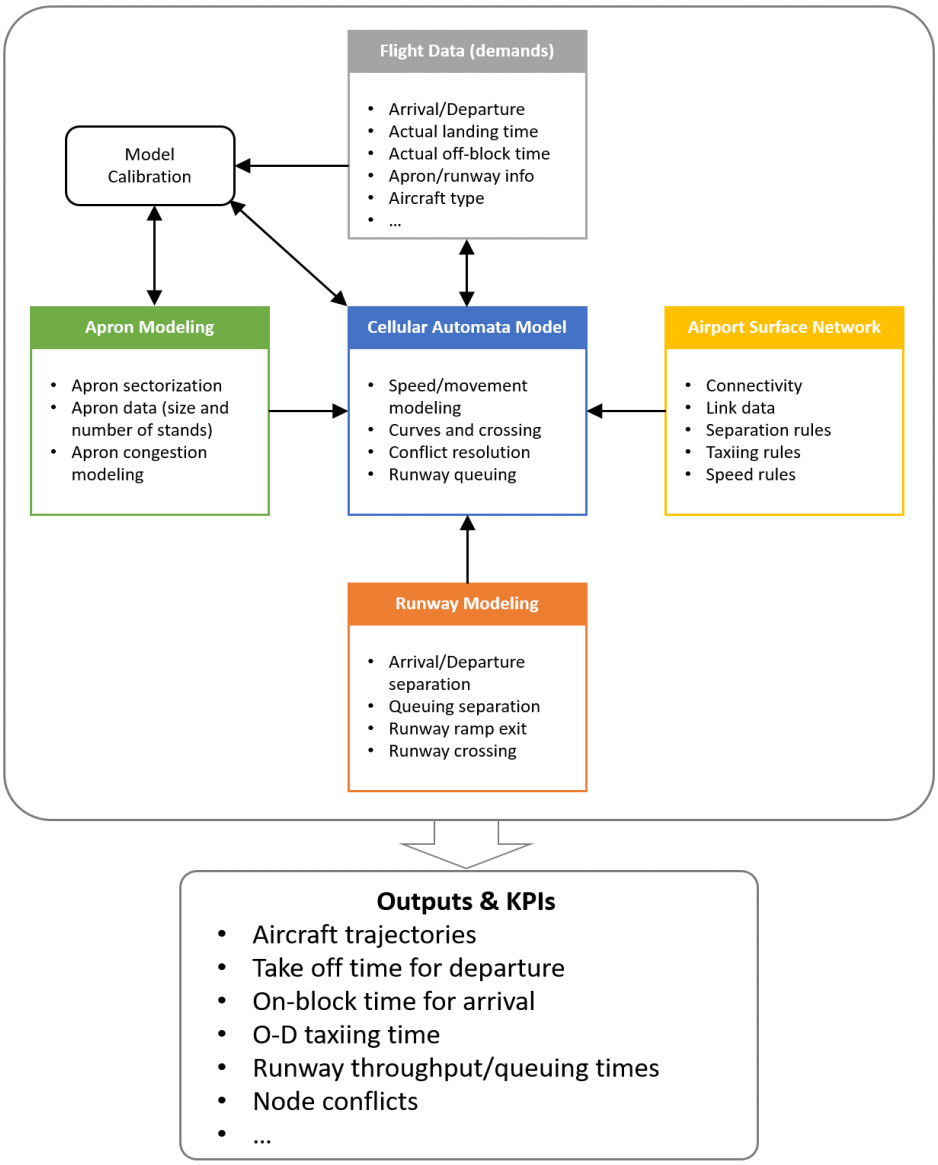

Figure 8.6. Flowchart of the A-CA modelling

8.3.1.1 Network graph generation

The airport surface is expressed as a transport network represented as a graph with (directed or undirected) links and nodes. Each taxiway consists of a series of single-directed or bi-directed links, while the intersections or crossing points are represented as nodes. Each node pair represents one directed link, in the case of bi-directed links, two links is used to represent the taxiway (one in direction), for example (see Figure 8.7), link M is represented as node 3 and node 4, along with the length, while link N consists of node 4 and node 3, along with the same length as the link M. If the aircraft moving along the link P and link M, its path is represented as […1,3,4…], and the distance of the path is calculated based on each distance of node pairs. Google Earth is used to measure the taxiway lengths and the apron size in the surface network.

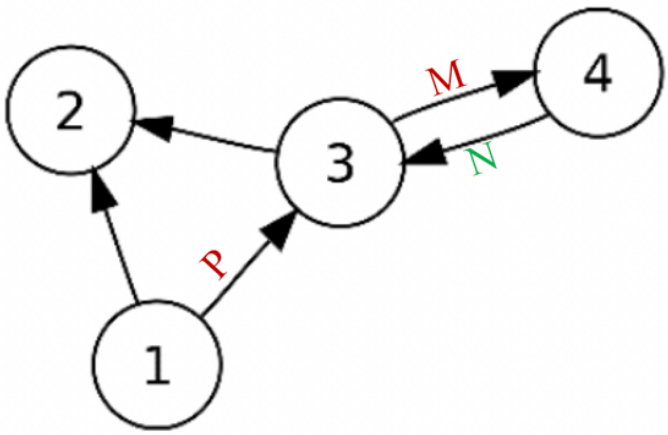

Figure 8.7. Example of directed links

8.3.1.2 Taxiing modelling

At PEK Airport, each aircraft normally follows the standard taxiing route between each O-D pair, unless conflicts are envisaged in advance or the aircraft deviates from the assigned route, the controller then chooses alternative routes to resolve the conflict. This standard taxi routes along with the OD pair derived from the historical data are set up as the *Base Case* of the proposed A-CA simulation. In the *Test Case* of the A-CA simulation model, all feasible taxiing routes are listed according to the operation rule and the interview of SMEs, and then the dynamic path search is calculated by the proposed optimisation algorithm aiming at improving operation efficiency on the airport surface. During the taxiing process, due to the wake turbulence, each aircraft moving on the surface should follow the minimum separation rules depended on the aircraft type pair shown in Table 4.1.

The taxiing route on the surface network is composed of links of the graph, connecting one link to the following link at different nodes, and each aircraft passing through the network is assigned an origin-destination (O-D) pair and route to follow. While the aircraft is advancing and is approaching the end of the current link, it continues moving to the beginning node of the following link automatically according to the assigned path consisting of the designated links. Paths in the A- CA simulation is defined using a 1D array where the sequence of nodes specified as $[n_1, n_2, n_3, \dots n_m]$, where n_1 and n_m are represented as the origin and the destination of the path. In addition, due to different speed at curves and straight taxiway, all curve nodes included in the path nodes are listed. Therefore, the path data used in the simulation is shown as $P = \{[n_1, n_2, n_3, \dots n_m]\}$, along with $Curve = \{[n_{k,} \dots, n_p]\}$. In the *Base Case* simulation, the taxiing route between each O-D pair is default, where for departures, aircraft located in the same O-D pair follows the same taxiing route to the runway threshold, while for arrivals, the specific route of each O-D pair (runway exit on the designated runway to the apron) is listed, the aircraft follows the path randomly constrained by the aircraft type and whose corresponding possibility, while in the *Test Case,* all admissible routes between each O-D pair is listed.

8.3.1.3 Speed rules

At PEK airport, taxiway segments (represented as links in the simulation) are constrained by a set of maximum taxiing speeds. These include the normal taxiway speed, towing/pulling speed, main taxiway speed, and runway exit speed. Due to the specific movement within the apron is not considered, but instead of a node with different aggregate time constrained by the congested level, the apron attribute and flight type (departure or arrival), the maximum normal taxiway speed (20 knot), turning speed (10 knot), maximum apron speed (10 knot) and runway exit speed (10knot) are considered in the simulation, which convert to the speed shown in Table 8.1. Here, as aircraft needs to make a turning at the runway exit, so the speed at where will be considered as a curve (5 cells/unit time) in the simulation. The maximum speed is a constraint in the simulation, which is not allowed to exceed while accelerating, but the speed for each flight is updated and assigned at each time step depending on the current situation on the airport surface network.

Table 8.1. Speeds of the model. (Units: cells/unit time)

v_{max}	10
v_{curve}	5
v_{apron}	5

8.3.2. Apron Modelling

Unlike the detailed movement on taxiways modelled in the A-CA model, aprons are treated as nodes but with aggregate times computing the required time of movement within each apron at each time step.

8.3.2.1. Basic parameters of the apron

Table 8.2 shows the basic parameters of the apron, including the length and the number of stands located in the corresponding apron. Google Map is used to test the length of the apron.

Table 8.2. Basic parameters of the aprons

Aprons	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Length (m)	870	480	350	950	990	350	450	950	450	990	1100	480	370	740
Number of stands	11	4	5	20	15	22	30	15	18	7	4	13	9	11
Aprons	15	16	17	18	19	20	21	22	23	24	25	26	27	
Length (m)	890	600	920	250	480	860	739	890	670	790	750	490	360	
Number of stands	14	6	14	20	9	10	5	8	12	13	8	11	11	

8.3.2.2. Modelling of taxi time within aprons

As the aforementioned, the specific movement within in the apron is not modelled in this A-CA model but will be considered as the aggregate time and the apron attribute (i.e. the number of stands in the apron, apron size). This aggregate time represents the required time from the aircraft enters the apron to the in-block time for arrivals, or from the off-block time to the engine-on time on the taxiway network for departures. The taxi time for both departure and arrival aircraft within each apron is expressed as (8.1).

$$t_{apron} = \left(\frac{L}{2V_{apron}} + T\right)\left(1 + \frac{\alpha(ops + 1)}{N}\right) \tag{8.1}$$

Where

L is the size of the apron;

V_{apron} is allowable maximum speed within the apron area;

T is an initial and final manoeuvre time;

α are apron congestion factors including 27 different values corresponding grouped 27 aprons in this research;

ops is the number of aircraft moving in the apron at the time t; and

N is the number of stands in the apron.

The first part of this equation means the minimum time required moving in the apron from enters to the stand or vice versa. $\frac{L}{2V_{apron}}$ means the minimum taxiing time from enter to the stand or vice versa, and T represents the required time in the final parking manoeuvre for arriving aircraft, and initial manoeuvre for departing aircraft. For example, the time of starting up engines, taxiing clearance issued, and final check before taxiing. Obviously, T for departures is much longer than for arrivals and the two values are determined by the statistics data and ATC survey. The second part $(1 + \frac{\alpha(ops+1)}{N})$ is trying to add congestion factor to meet the real operation. ops is the number of the aircraft that are taxiing within the apron at the time t, this value is updated at each time step. N is a constant value, and corresponds to each apron. α is an indicator and various, by taking into account the specific characteristics of each apron. If many aircraft moving in the apron at time t, the aircraft would spend much longer time to taxiing out the apron. In short, t_{apron} is various at different time and different aprons, which depends on the number of operations happening within the apron at current time.

8.3.3. Runway Modelling

Although runway is modelled as a node in the simulation, the required operation rules are considered as constraints. As aforementioned, the runway is the origin for arrivals and the destination for departures. In the A-CA model, the runway operation rules, as well as the runway entry nodes (as the runway threshold that used for runway queuing for departures) and runway ramp exit nodes (as origins for arrivals) are defined, respectively.

Here, the runway operation direction is north, since the prevailing direction of the runway operation at PEK Airport is north (up to 82% per year according to one-year data statistics and ATC survey), with runways being designated 01, 36R and 36L, respectively. The operation mode at PEK is mixed (three runways were operated independently, and each runway are both for arrival and departure).

8.3.3.1 Runway separation

Aircraft usually stop and wait for ATC clearance at the holding point prior to the entrance of the runway. When there is a non-zero departure queue, the aircraft needs to stop further away to maintain minimum separation (50 m) with other aircraft in the queue. The deceleration rule is employed to control the speed of the aircraft when approaching the holding point or the end of the queue.

Due to the wake turbulence, runway operation separation in terms of successive departure separation, successive arrival separation and mixed departure and arrival separation should be considered. Specifically, a minimum time headway h_{takeoff} is enforced between two consecutive takeoffs. Furthermore, as the runway is used for both take-off and landing, a minimum time separation h_{land} is maintained between a takeoff and landing. Additionally, an aircraft must have vacated the runway after landing before a departure to be given clearance, the duration of the landing run is denoted $h_{\text{exit ramp}}$. The following inequalities must hold for a queuing aircraft to be given clearance at time t:

$$t > t_{\text{previous takeoff}} + h_{\text{takeoff}} \tag{8.2}$$

$$t + h_{\text{land}} < t_{\text{next landing}} \tag{8.3}$$

$$t > t_{\text{previous landing}} + h_{\text{exit ramp}} \tag{8.4}$$

where, in the case of PEK, the values of $h_{\text{exit ramp}}$ is set as 50 seconds, and the h_{takeoff} and h_{land} depends on the aircraft type pair shown in Table 8.3 and Table 8.4, respectively.

Table 8.3. Minimum wake turbulence separation rule for consecutive departures (unit: seconds)

Type of leading aircraft	Type of trailing aircraft		
	Light (L)	Medium (M)	Heavy (H/SH)
Light (L)	120	120	120
Medium (M)	120	120	120
Heavy (H/SH)	120	120	180

The separation for consecutive arrivals should maintain once the aircraft entry the approach period, which is controlled by controllers via order issue. In this research, the arrival time and spatial are not optimised, in which, the runway usage is derived from the history data, and the actual arrival data with a random possibility is used in question. This is because the arrival operation is determined in the approaching period, which is beyond the scope of airport surface in my research. Furthermore, this separation has been implied in the historical flight data, and an arrival aircraft has a priority to the departure aircraft in real-world operation.

When a departure following by an arrival, once the aircraft lifts up from the runway, the arrival aircraft can be landing and touchdown. On the other hand, when an arrival following by a departure, as long as an arrival exits from the runway, the departure aircraft can speed up and then take off. Here, the values of $h_{\text{exit ramp}}$ and $h_{\text{occupancy}}$ are set as 50 seconds, this is determined by statistics and has been agreed with the ATCOs.

Table 8.4. Minimum wake turbulence separation rule for consecutive arrivals (unit: kilo-meters)

Type of leading aircraft	Type of trailing aircraft		
	Light (L)	Medium (M)	Heavy (H/SH)
Light (L)	6	6	6
Medium (M)	10	6	6
Heavy (H/SH)	12	10	8

8.3.3.2 Runway exits

For arrivals, only the assigned runway is given in the flight data, the ramp exit of the runway used by the aircraft is not known. The speed limit of the runway exit is 30kt, if the aircraft speed is reduced to lower than the speed limit, the aircraft can exit the runway from the nearest runway exit point. In this case, the arrival flight in question is assigned the ramp exit randomly based on the aircraft type and its corresponding possibility. Exits of each runway refer to Figure 8.8. The probability of each runway exit is shown in Table 8.5, the values are set according to the experience of the ATC staff at PEK airport surface. Take RWY 01 as an example, there are three runway exits numbered nodes Q5, Q6 and Q7. The probability of SH, H and M/L aircraft type for the runway exit are 5%, 10%, and 85%, respectively. Notably, the middle runway, named RWY 36R has four exits, two of which (E5 and E6) are used for the exit of flights destinated to the apron in the east airport, while the remaining two exits (W5 and W6) are used for the exit of flights destinated to the apron in the west airport. For each part of runway exits (1st East and 2nd East, and 1st West and 2nd West) on the RWY 36R, the sum of the probability corresponding to three types of aircraft is 1.

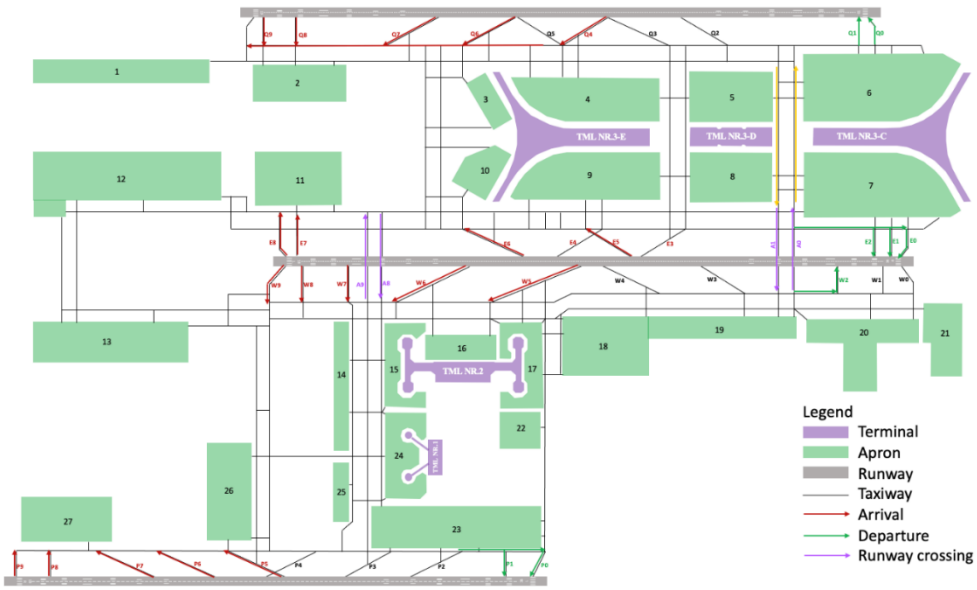

Figure 8.8. Airport surface modelling at PEK

8.3.3.3 Runway entrance

The runway entry nodes which connected to the runway, are given according to the operation rules of Beijing Airport, every flight should follow the assigned path and wait for takeoff at the designated runway threshold, which is also included in the node of the path data for the flight.

Except for some special aircraft type, each departure can choose to take off land from the displaced threshold points. The runway and corresponded displaced threshold point at PEK are shown in Table 8.6, for the location on the surface refers to Figure 8.8. However, for some extremely large aircraft (i.e. B747-8, A380), they have to use the full runway to take off or land, and only designated can be used.

Table 8.5. Exit probability for each aircraft type on each runway

RWY	RWY Exits	Distance to the exit (m)	The category of the aircraft		
			SH	H	M/L
01	1st(Q5)	1500	5%	10%	85%
	2nd(Q6)	2000	20%	60%	20%
	3rd(Q7)	2500	65%	30%	5%
36R	1st(E5)	1500	5%	10%	85%
	2nd (E6)	2250	85%	90%	25%
	1st(W5)	1750	5%	10%	85%
	2nd(W6)	2500	85%	90%	25%
36L	1st(P5)	1500	5%	10%	85%
	2nd(P6)	2000	20%	60%	20%
	3rd(P7)	2500	65%	30%	5%

Table 8.6. Runway entrance and displaced threshold point at PEK

Runway	Runway entrance and Displaced threshold point
36L	P0, P1
01	Q0, Q1
36R	E0, E1, E2, W1

8.3.3.4 Runway crossing

Runway crossing can be observed on the airport surface of PEK due to limited runway resource and stand attributes, which means that some aircraft must cross the Middle Runway (36R/18L) to their assigned aprons for dock, or to their assigned runways for take-off. Such crossing movements inevitably effect runway operation efficiency and would result in flight delays and congestions near the runway crossing points, especially in peak hours, as well as compromising safety whilst crossing. In 2017, the volume of flights was up to 597,000, which was around

1800 flights operated per day, in which, over 20% flights happened crossing movements, according to the one-year empirical data statistics.

8.3.4. Aircraft Activation

An arrival aircraft is activated as input of the A-CA model when it lands on its designated runway. The time of activation is defined to be the initial time. Similarly, a departure aircraft is activated when it is pushed back. The time of activation is also defined to be the initial time. At the time of activation, each aircraft is automatically assigned a route, which connects its origin (for departures, the apron; for arrivals, the runway ramp exit[19]) to the destination (for arrivals, the apron; for departures, the runway end). During the activation period, the aircraft cruises through the taxiing network along the pre-determined route, and engages with other activated aircraft, when relevant, in terms of apron congestion, conflict resolution, and runway queuing. The aircraft of interest is deactivated when it reaches its destination.

8.3.5. Empirical Data of PEK Airport

A total of 597,000 empirical data for one year from January 2017 to December 2017 was collected from the Airport Operation Centre (AOC) of PEK Airport. Each data entry consists of 52 items, which includes basic flight information (e.g. flight data, airlines, flight No. Aircraft type, the number of passengers), key node times within the airport (e.g. check-in open/end time of the flight, bridge-on and bridge-off time, gate open/closed time, boarding and the end boarding time, on-block and off-block time) and specific operation time (e.g. planned time, estimated time of arrivals and departures, actual time of arrivals and departures, runway usage,

[19] Note that, each arriving aircraft is randomly assigned a runway ramp exit according to a given probability distribution; see Table 8.5.

stand usage, departure time of the previous flight and arrival time of the following flight). Some items of the flight data are listed below.

Flight Data	**Planned time**
Flight Registration Number	Scheduled Time of Departure (STD)
Airline Code	Scheduled Time of Arrival (STA)
Flight Number	Actual Landing Time (ALDT)
Arrival/Departure	Actual Take-Off Time (ATOT)
Aircraft Type	Actual In-Block Time (AIBT)
International/domestic	Actual Off-Block Time (AOBT)
Apron usage	Bridge-on Time
Runway usage	Bridge-off Time
Number of passengers	Boarding gate open time
Designated terminal	Boarding gate close time
Fueling start/end time	
Cleaning start/end time	

The baseline simulation is for 14th September 2017, which is a typical day with a representative demand profile. The operation mode is mixed (three runways were operated independently, and each runway are both for arrival and departure), and the operation direction is north for all day, which corresponds to the runways named 01, 36R and 36L. The number of flight plan on 14th September 2017 is 1773, 16 flights of which were cancelled, the remaining 1757 flights were all applied to the simulation. The demands of arrivals and departures of each hour according to the flight plan is shown in Figure 8.9.

The category of the aircraft in question is classified based on the aircraft Maximum Take-Off Weight (MTOW) proposed by the ICAO (ICAO, 2001), plus one special aircraft type named Super Heavy (SH), which only refers to Airbus 380 and Boeing 747-8 in this model, as these two types of aircraft moving on the airport surface is constrained because of the extra-long wingspan.

- Light (L) aircraft type with MTOW of 7,000 kg (15,500lb) or less;
- Medium (M) aircraft type with MTOW less than 136,000kg (300,000lb) and more than 7000kg (15,500lb);
- Heavy (H) aircraft type with MTOW of 136,000 kg (300,000lb) or more; and
- Super Heavy (SH) refers only to Airbus 380 and Boeing 747-8.

The aircraft categories above listed and their corresponding aircraft types, as well as other aircraft basic information, which are employed as inputs in the A-CA model, refer to Appendix 3.

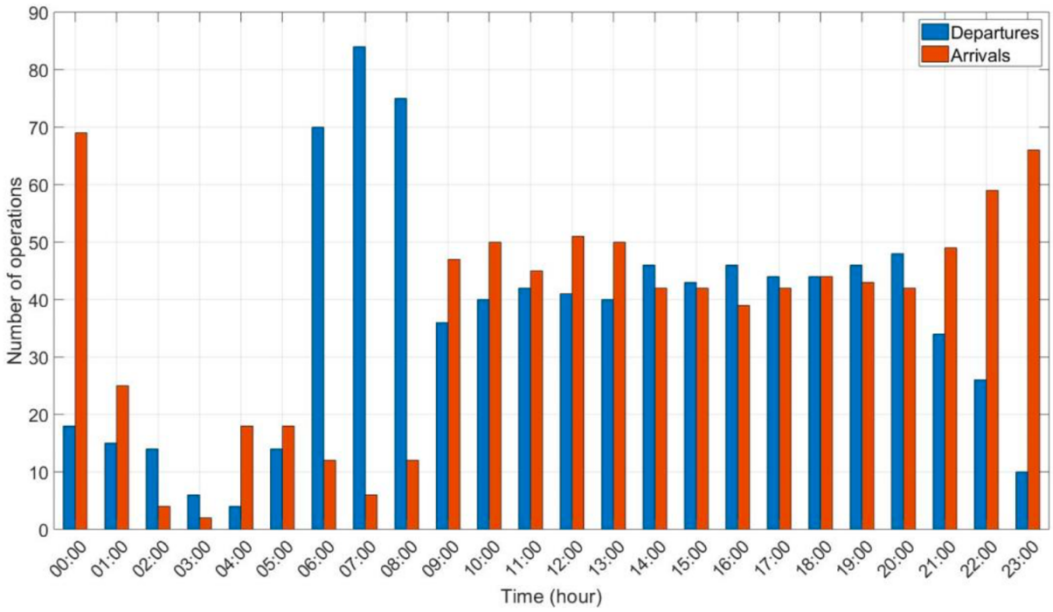

Figure 8.9. Scheduled flight plan on 14/09/2017 at PEK

The data for the 1757 flights within the simulation include 9 attributes, the details are shown below.

No.	Attributes
1	Initial time
2	Origin node

3	Destination node
4	Final time
5	Number of cells occupied by the aircraft (aircraft size)
6	Aircraft category
7	Arrival or departure
8	Scheduled time of departure (only for departures)
9	Indicates if the empirical data is used for validation or not

8.3.6. Model Calibration and Verification

The A-CA model needs to be calibrated, as the available flight data only contains key time stamps (e.g. ALDT, ATOT, AIBT, AOBT) whereas detailed movement data within the taxiway are unavailable. Therefore, the purpose of the calibration is to reach optimal matching between the aforementioned key time stamps and the model outputs. The parameters to be fine-tuned during this process include apron congestion coefficients (recall that the aprons are treated as nodes with congestion effects), minimum separation parameters for runway usage (including runway incursion). Due to the presence of uncertainty in the model, a batch of random simulations are performed with 10 independent runs for one day of empirical data. In what follows, the results of two baseline dates are presented, and 10 independent A-CA simulation runs are performed for each date.

1) Average taxiing times departures and arrivals

The simulation is for 14th and 17th September 2017, which are typical days of operation with a representative demand profile; the runway operational mode is the north and the weather are similar for both dates. Here the average taxiing time on the entire airport surface for all the flights during one day of operation is considered. The average taxiing times produced by the model are compared with the empirical taxiing times. The root mean square errors and symmetric mean absolute percentage errors are shown in Table 8.7 for 14th Sep and Table 8.8 for 17th Sep.

Table 8.7. Error summary for average taxiing time for the A-CA model (14th Sep)

	Error Indicators	Value
RMSE	Average Taxiing Time (arrivals)	0.27 (min)
	Average Taxiing Time (departures)	0.09 (min)
SMAPE	Average Taxiing Time (arrivals)	2.23%
	Average Taxiing Time (departures)	0.4%
	Runway throughput (cumulative)	0.85%

Table 8.8. Error summary for average taxiing time for the A-CA model (17th Sep)

	Error Indicators	Value
RMSE	Average Taxiing Time (arrivals)	0.7 (min)
	Average Taxiing Time (departures)	0.13 (min)
SMAPE	Average Taxiing Time (arrivals)	5.1%
	Average Taxiing Time (departures)	0.59%
	Runway throughput (cumulative)	0.86%

On 14th Sep, the average taxiing-in and taxiing-out time are 13.47min and 21.89min, respectively. The simulated average taxiing-in time and taxiing-out time are 13.17min and 21.8min.

On 17th Sep, the average taxi-in time and taxi-out time are 13.37min and 20.27min, respectively. The simulated average taxi-in time and taxi-out time are 12.68min and 20.15min.

3) Runway throughput

Runway throughput is a KPI representing the operational capacity of the airport surface (ICAO, 2011). As there are three runways, their individual throughputs as well as combined total throughputs are compared with simulated throughputs. The results are shown in Figure 8.10 for 14th Sep, and in Figure 8.11 for 17th Sep.

The highly consistent trends between the simulated and empirical curves in Figure 8.10 and Figure 8.11 suggest that the simulation reasonably captures the airport's capacity at a

macroscopic level. The SMAPEs for the error in simulating total throughput is 0.85% for 14th Sep, and 0.86% for 17th Sep.

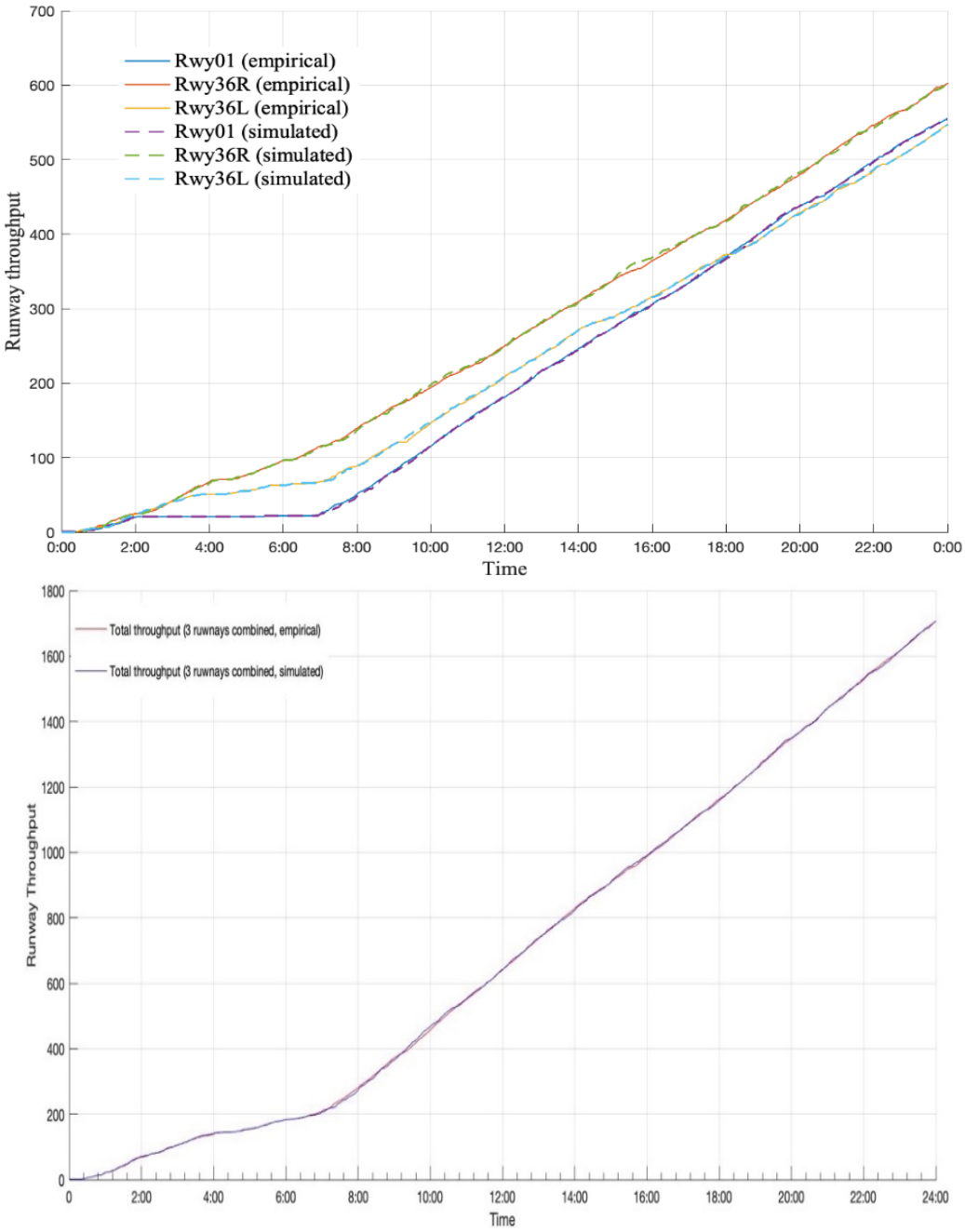

Figure 8.10. Cumulative runway throughput: three runways combined (top); each runway (bottom), on 14th Sep.

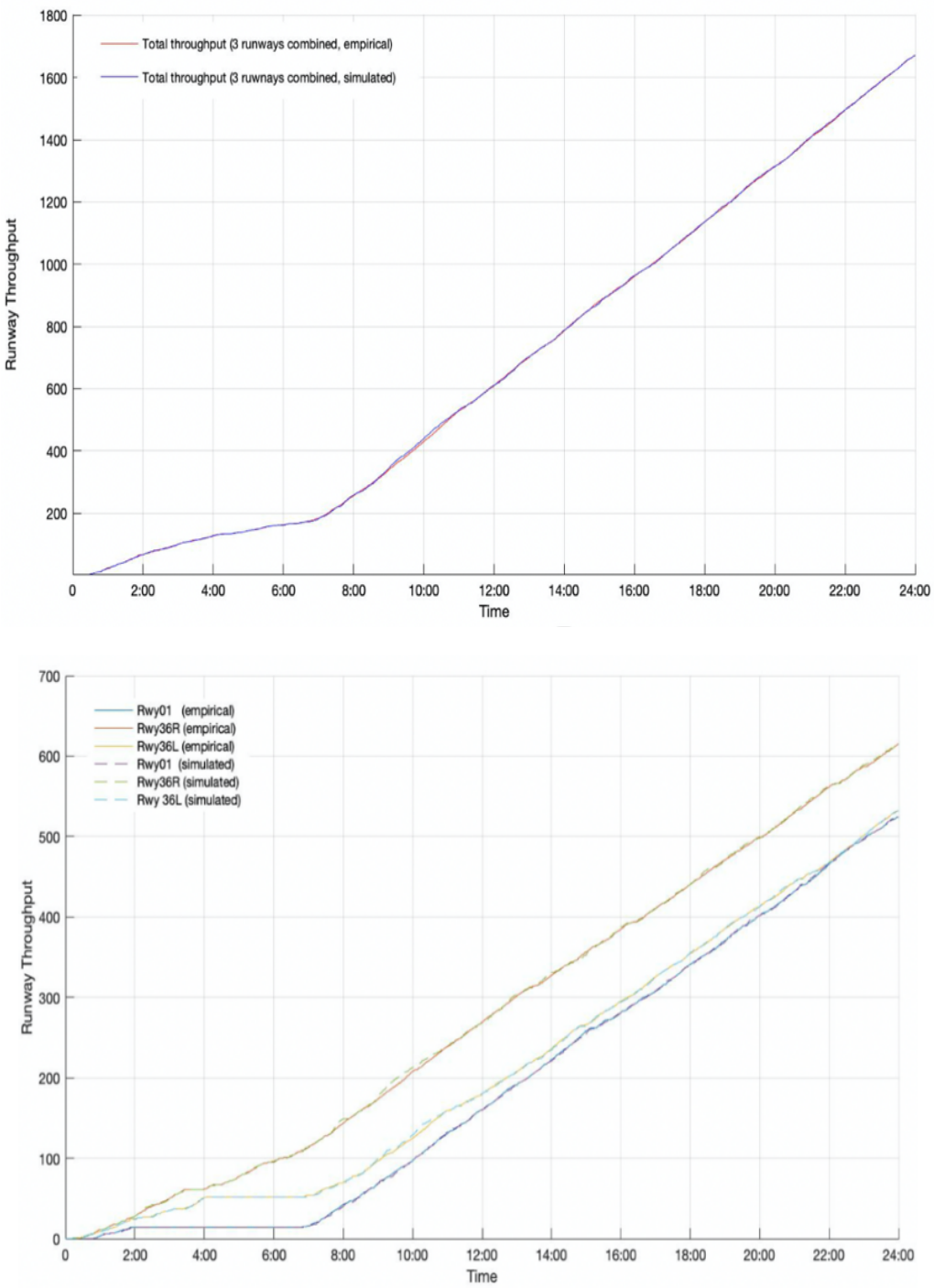

Figure 8.11. Cumulative runway throughput: three runways combined (top); each runway (bottom), on 17th Sep.

8.4. RESULTS OF INTEGRATED APRON-RUNWAY ASSIGNMENT

8.4.1. Results Based on Key Performance Indicators

In this section, the A-CA simulation is set up to evaluate the performance of the proposed new assignment. Given the built-in randomness of the A-CA simulation, for each comparison scenario (i.e. current and new assignment), 10 independent simulation runs are performed, followed by a hypothesis testing with a 90% confidence level to determine the statistical significance. This comparative approach is commonly seen in simulation tests with built-in random variables (Mascia et al., 2016). All the comparative results shown in Table 8.9 are statistically significant.

In terms of taxiing time reduction, the level of improvement, although considerable, is lower than that for distance reduction (see Table 8.9). This is due to the congestion encountered on the taxiway network, during runway queuing, and within apron areas. In terms of runway queuing, due to the congestion-aware runway assignment procedure, which balances the utilisation of all three runways, the mean queuing time and maximum number of queuing flights have decreased significantly. In particular, RWY01, which has the highest throughput during daytime operation, has experienced a drastic reduction of congestion after the new assignment (by 44.4% and 56.5% for queue length and queuing time, respectively). This is confirmed in Figure 8.12, where the total throughputs of the three runways after the new assignment are much more balanced than the current operation. Box plots of the maximum queuing length and mean queuing times resulting from 10 independent simulation runs, are shown in Figure 8.13.

Table 8.9. Key performance indicators from ACA simulation based on the current and new apron-runway assignment.

KPIs		Current assignment (min)	New assignment (min)	Improvement (%)
Average taxiing time (incl. queuing, apron delays)	**Combined**	16.51 min	15.48 min	6.2
	Arrival	11.75 min	11.31 min	3.7
	Departure	21.26 min	19.63 min	7.7%
Runway queuing [RWY01, RWY36R, RWY36L]	**Longest queue (# of aircraft)**	[7.2, 6.6, 4.2]	[4.0, 6.1, 4.0]	[44.4%, 7.6%, 4.8%]
	Mean queuing time (min)	[4.6, 1.7, 2.5]	[2.0, 1.4, 1.9]	[56.5%, 17.6%, 24%]
Total number of conflicts		382.6	306.8	19.8%
Percentage of gate assignments		68.0%	76.0%	11.8%

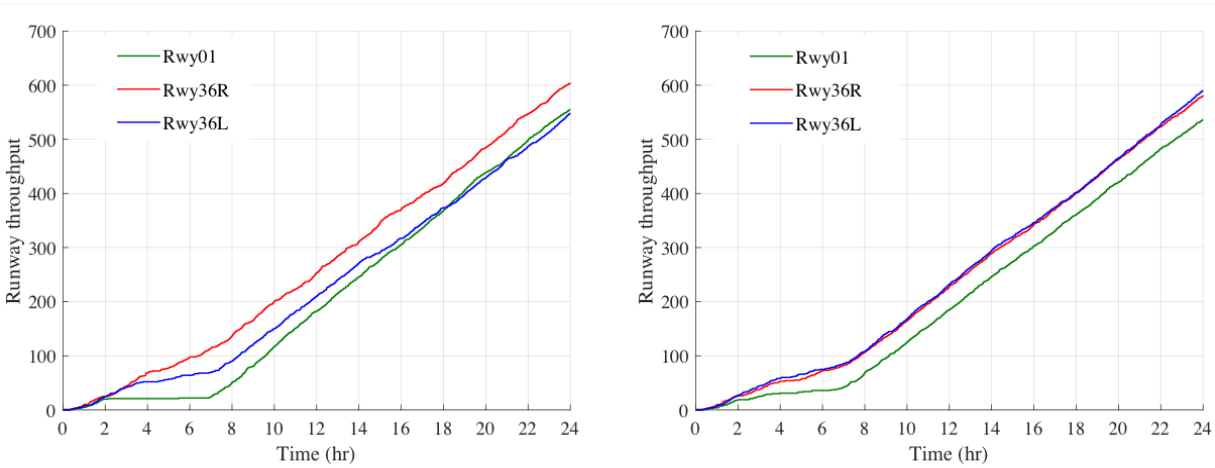

Figure 8.12. Runway throughputs (incl. arrivals and departures) before and after the apron-runway assignment

It is also noted that with the decrease in taxiing distance, taxiing time and conflicts, the fuel consumption and emissions are expected to decrease as well. As a detailed model for calculating fuel use and emissions requires detailed aircraft information (e.g. engine thrust) and taxiing dynamics (e.g. speed, acceleration, deceleration, idling), which is beyond the modelling scope of our work, here a relatively macroscopic model is used for a rough estimate of the reductions in fuel consumption and emissions. Following Levine and Gao (2007) and Guo et al. (2014), the following widely used formulae were adopted for fuel consumption F_i and emission E_i of aircraft i:

$$F_i = \sum_k TIM_{ik} * FF_{ik} * NE_i$$

$$E_i = \sum_k TIM_{ik} * FF_{ik} * NE_i * EI_{ijk}$$

Where

TIM_{ik}: time spent by aircraft i in mode k (taxi-out, taxi-in);

FF_{ik}: fuel flow index in mode k for each engine of aircraft i;

NE_i : number of engines on aircraft i;

EI_{ijk}: emission index for pollutant j (NOx, CO, HC);

It is noted that the above formulae distinguish between two modes (taxi-in and taxi-out). In Levine and Gao (2007), the same engine trust level of 7% is assumed for both taxi-in and taxi-out operations. In terms of number of engines, Category 1 (super heavy) aircraft have 4 engines, and the other types have 2. The time in model TIMik is provided by the ACA simulation for taxi-in and taxi-out aircraft. We may now calculate the relative reduction of fuel consumption and emissions as in Table 8.10.

Table 8.10. Reduction of fuel consumption and emissions from the new apron-runway assignment ($\delta_1^{Arr} = -20, \delta_2^{Dep} = 40$).

	Fuel Consumption			Emissions
	Arrival	Departure	Total	(NOx, CO, HC)
Reduction (%)	4.2	8.0	6.6	6.6

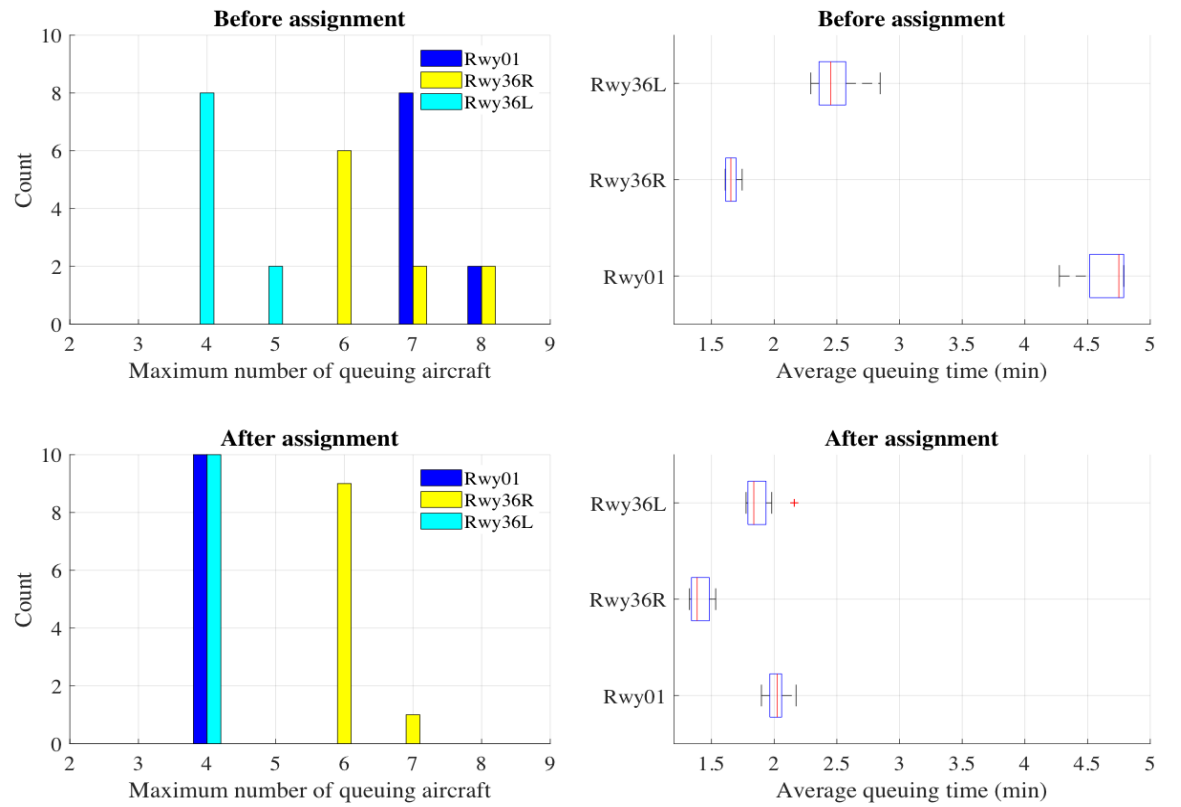

Figure 8.13. Box plots of maximum runway queuing and mean queuing times from 10 independent ACA simulation runs.

In terms of taxiing conflicts on the surface network, the proposed apron-runway assignment reduces the total number of conflicts by nearly 20%, as shown in Table 8.9. Figure 8.14 shows some nodes with significant conflicts before and after the apron-runway assignment, which is obtained from a particular A-CA simulation run. In both cases, the node at the runway end of RWY36R experiences heavy conflicts, as this runway is used mainly for departure. However,

the proposed design is able to reduce the conflicts there from 55 to 49. In addition, the taxiing conflict has been significantly reduced on the main taxiways to the west of RWY01 and Ryw36R. This shows that congestion-aware runway assignment brings tangible benefits to taxiing operations by reducing runway queuing as well as fluidity along arterial taxiways.

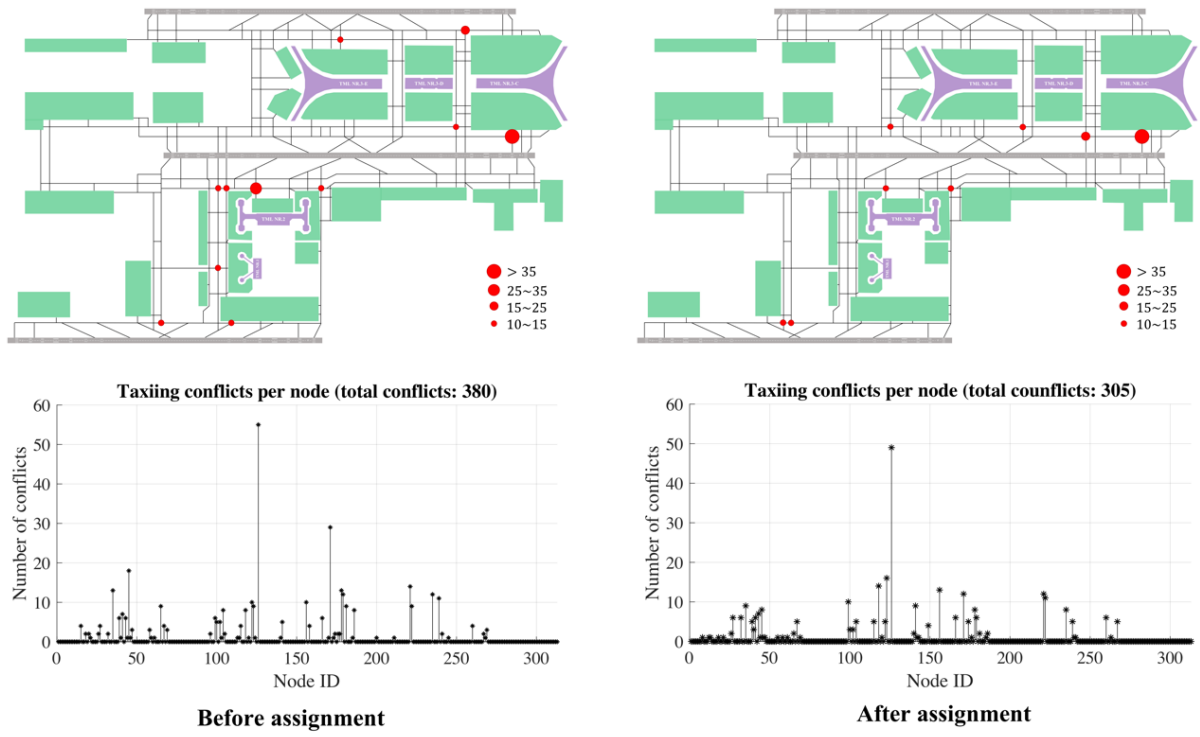

Figure 8.14. Conflict comparison before (left) and after (right) assignment

8.4.2. Determination of Calculated Off-block Times

The convergence of the proposed apron-runway assignment algorithm (Section 5.6.3) and the COBT algorithm (Section 5.6.4) is examined in Figure 8.15. The iterative apron-runway assignment algorithm converges quickly, which confirms the observation made in Remark 2. On the other hand, the iterative procedure for COBT determination is able to quickly reach a low percentage of flights that miss their runway slots within a few iterations, but stalls around 10% afterwards until the 13th iteration. This is due to the non-analytic network performance

function arising from the ACA model, which lacks the analytical properties that guarantee algorithm convergence (such as Lipschitz continuity, monotonicity). Similar issues with algorithm convergence can be found in traffic network modelling and dynamic traffic assignment (Han et al., 2015; Szeto et al., 2015).

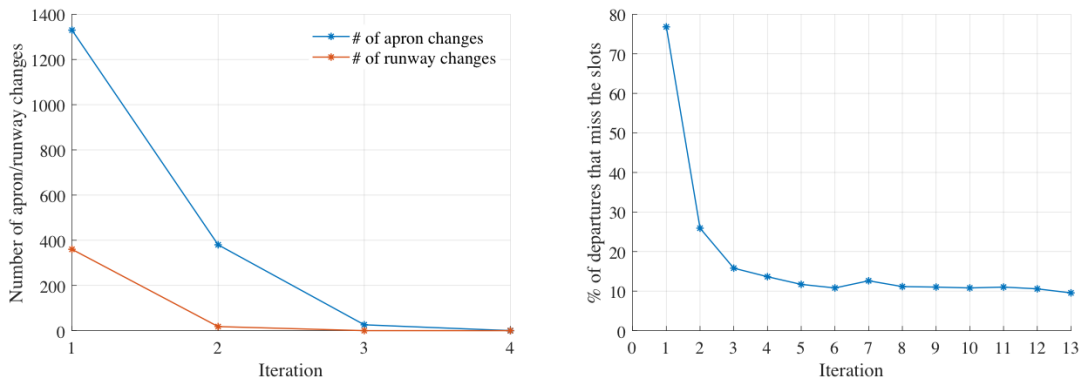

Figure 8.15. Convergence of the iterative apron-runway assignment (left) and COBT determination (right)

8.5. RESULTS OF IDRO OPTIMISATION

8.5.1. Dynamic Route Search

For dynamic route search, Algorithm 5 with a First- Come-First-Serve strategy is followed. That is, the route for each taxiing aircraft is determined based on network conditions at the time of its entry to the surface network. For each origin-destination (O-D) pair, the route set is pre-determined based on Standard taxiing route in PEK. Each route set contains a default route, which is used in the previous simulations in Section 8.4. The following sections summarise the performances of airport surface movement using A-CA simulation, where the default routing strategy is compared with the proposed dynamic route search algorithm.

8.5.1.1. Overall performance

In terms of the network-wide performance in terms of several key performance indicators (KPIs), the two routing strategies are compared in Table 8.11. In this table, the average taxiing time refers to the time spent from the aircraft's origin (either runway exit for arrivals, or apron exit for departures) to the destination (either apron entrance for arrivals, or runway end for departures); the taxiing time is further summarised for arrivals and departures. The average delay refers to the gap between the scheduled time and the actual time departures as the research scope is focusing on improving the efficiency on the local airport operation. In addition, arrivals have priority to the departures, and arrival delay is normally happened either in the en-route or within the previous airport. Finally, the number of conflicts occurred at nodes throughout the network (as defined in the A-CA model) is used as an indicator of network congestion and efficiency. It is also an indirect indicator of controller workload as instructions are constantly given to taxiing aircraft regarding forthcoming conflicts and means to resolve them.

Table 8.11. Comparison of default routing and dynamic route search in terms of KPIs (over 10 simulation runs).

	Ave. taxiing time	**Ave. taxiing time for arr.**	**Ave. taxiing time for dep.**	**Ave. delay**	**Total conflicts**
Default route	15.50 min	11.30 min	19.67 min	29.22 min	308
Dynamic route search	15.35 min	11.25 min	19.44 min	28.93 min	255
Improvement	0.97%	0.44%	1.17%	0.99%	17.21%

It can be seen from Table 8.11 that all five KPIs are improved when using the dynamic route search algorithm proposed in this work. In particular, the taxiing times for both arrivals and departures are slightly improved (around 1%). This is because the way route impedance is

defined mainly focuses on congestion and taxiing conflicts, rather than taxiing time, although the two are obviously related. When the network is near-saturated (which is the case for PEK), the room for shortening taxiing time is limited as the main bottleneck is runway queuing, which cannot be directly addressed by routing strategies. Table 8.11 shows a considerable reduction of total conflicts, as is expected from the definition of route impedance and the impedance-based routing strategy; this will be further elaborated in Section 8.5.1.3.

Figure 8.16-Figure 8.20 show the boxplots of the five KPIs for the default routing and dynamic route search strategies.

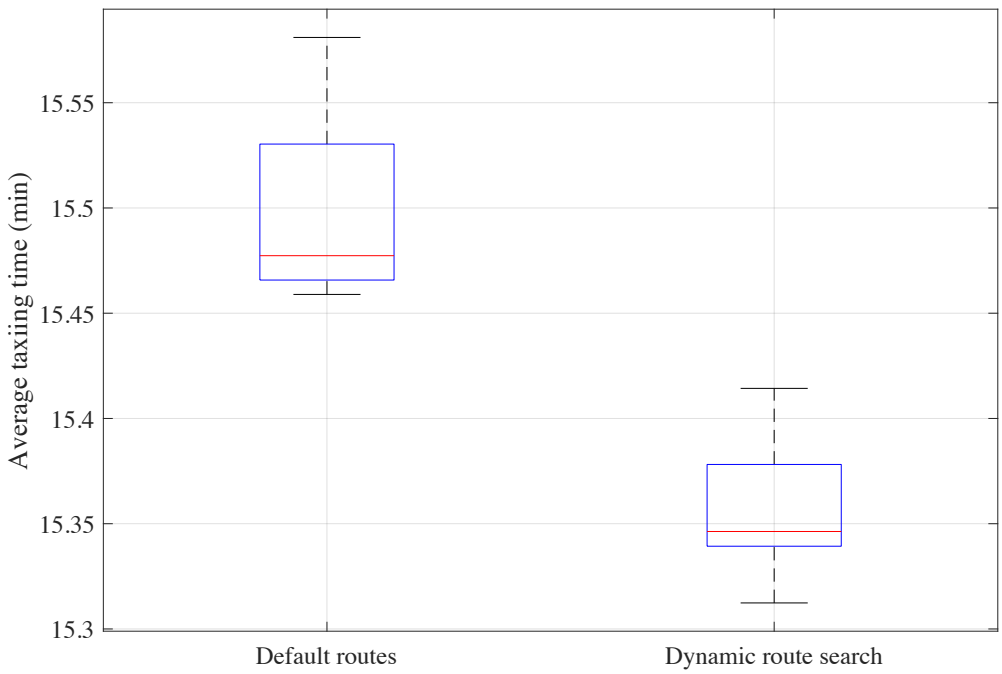

Figure 8.16. Boxplots (over 10 simulation runs) of average taxiing time for all flights.

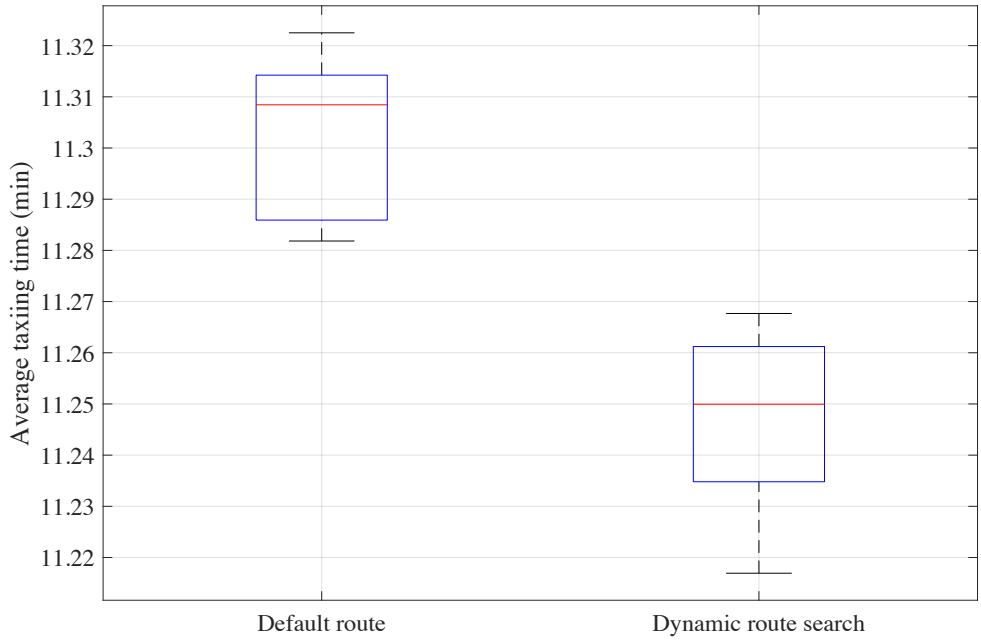

Figure 8.17. Boxplots (over 10 simulation runs) of average taxiing time for arrival flights.

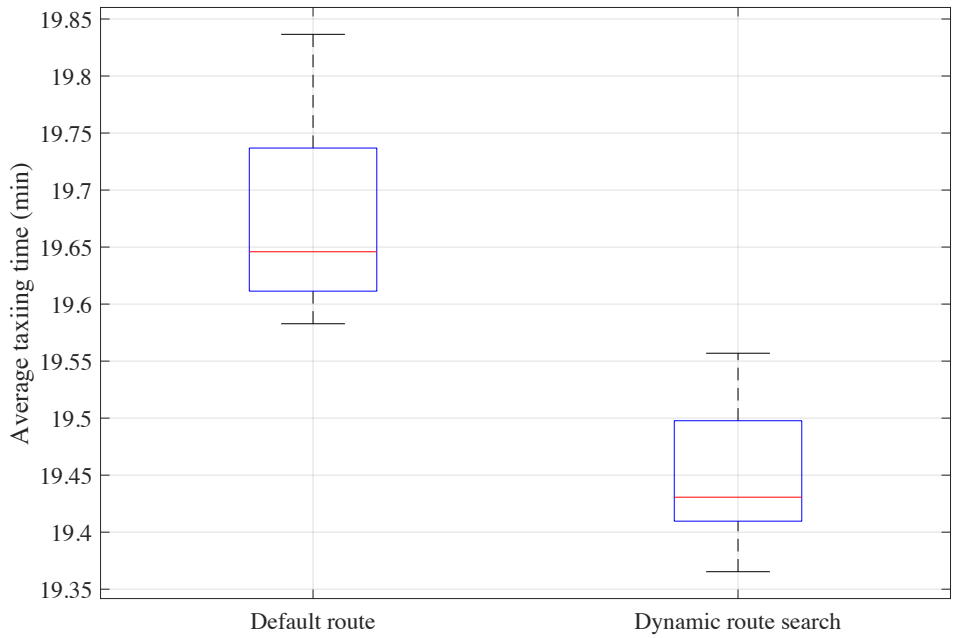

Figure 8.18. Boxplots (over 10 simulation runs) of average taxiing time for departure flights.

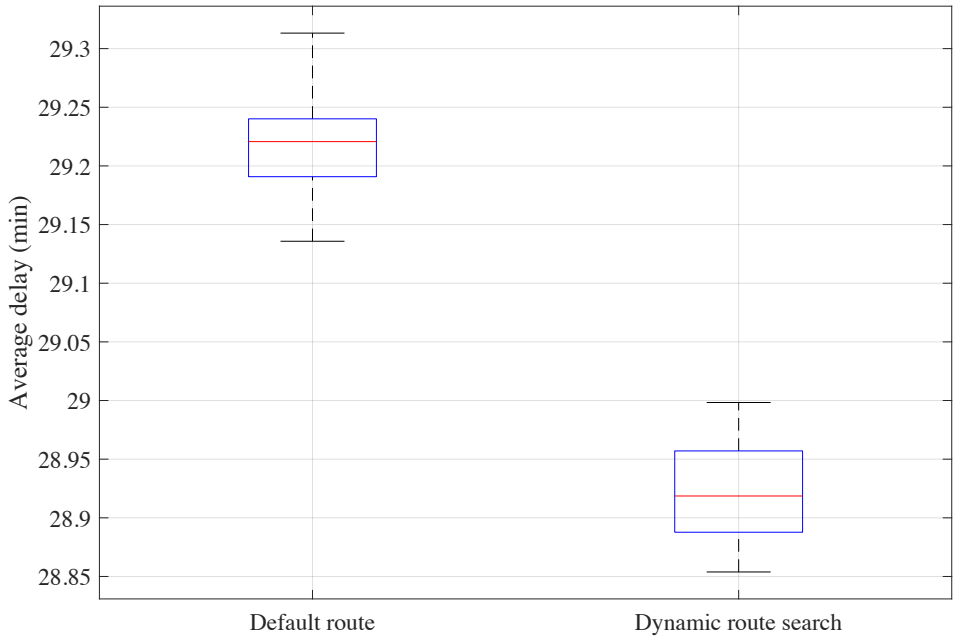

Figure 8.19. Boxplots (over 10 simulation runs) of average delay for all flights.

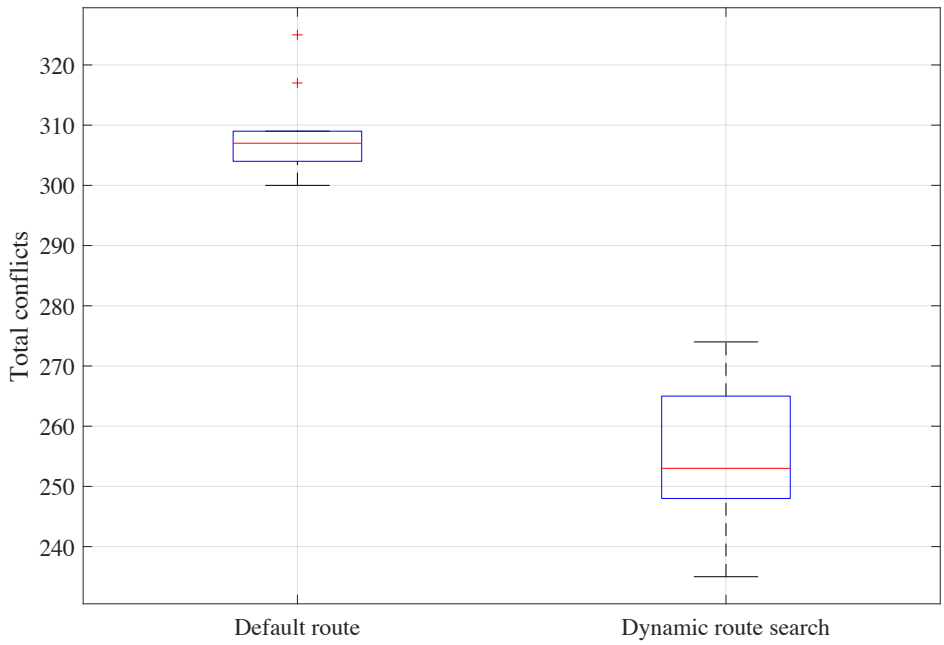

Figure 8.20. Boxplots (over 10 simulation runs) of total number of conflicts on the airport surface.

8.5.1.2. Reduction of route impedance

The aim of Algorithm 5 is to dynamically select routes from a given set of admissible ones, in order to minimise the expected route impedance based on real-time traffic conditions on the surface network. In this section, the reduction of route impedance is examined, compared to the default route selection, as a result of implementing Algorithm 5. To do this, the reduction of route impedance is calculated as:

$$\text{Reduction of route impedance} = \frac{(I_{\text{default}} - I_{\text{optimal}})}{I_{\text{default}}} \times 100\%$$

which is the relative reduction of the optimal route w.r.t. the default one. Such a quantity can be calculated for each aircraft, and

Figure 8.21, Figure 8.22, Figure 8.23 show the histogram of the impedance reduction for all the flights, arrival flights, and departure flights, respectively.

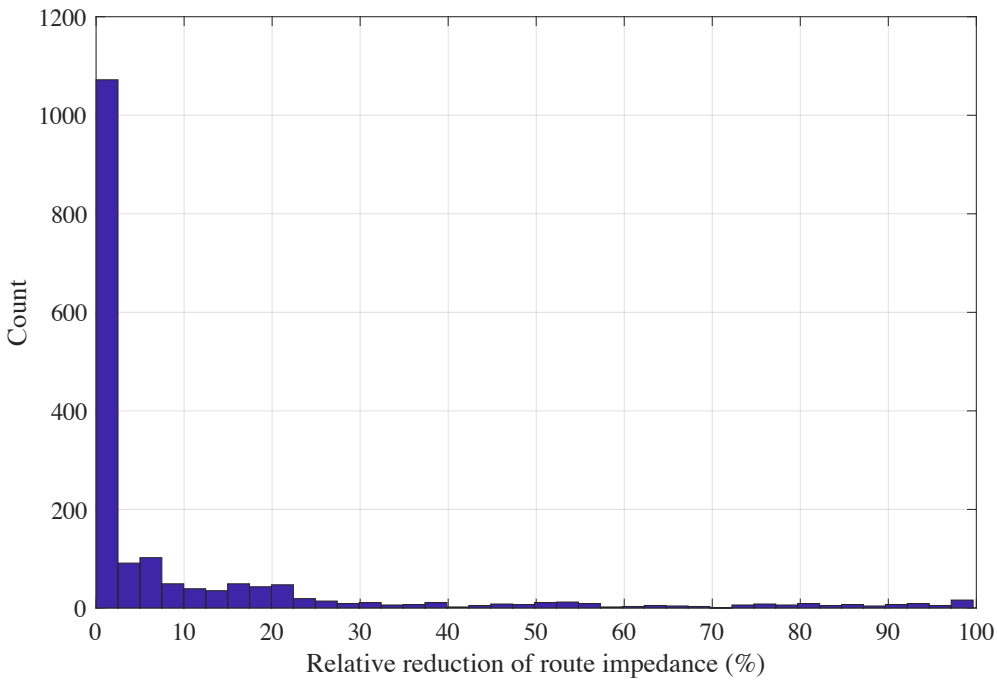

Figure 8.21. Histogram of relative reduction of route impedance for each aircraft

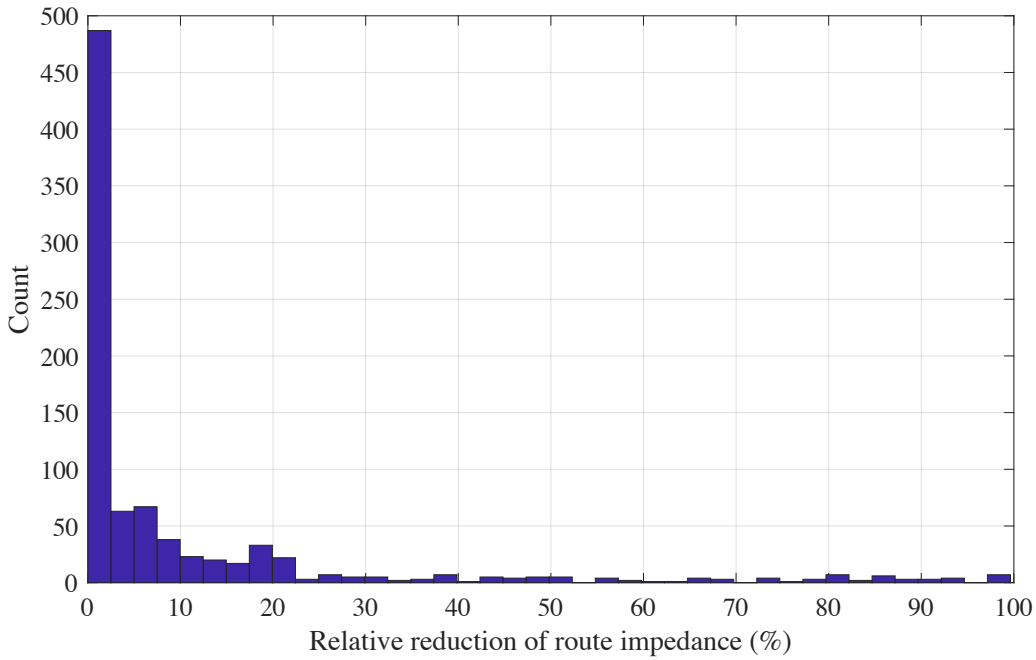

Figure 8.22. Histogram of relative reduction of route impedance for arrival aircraft

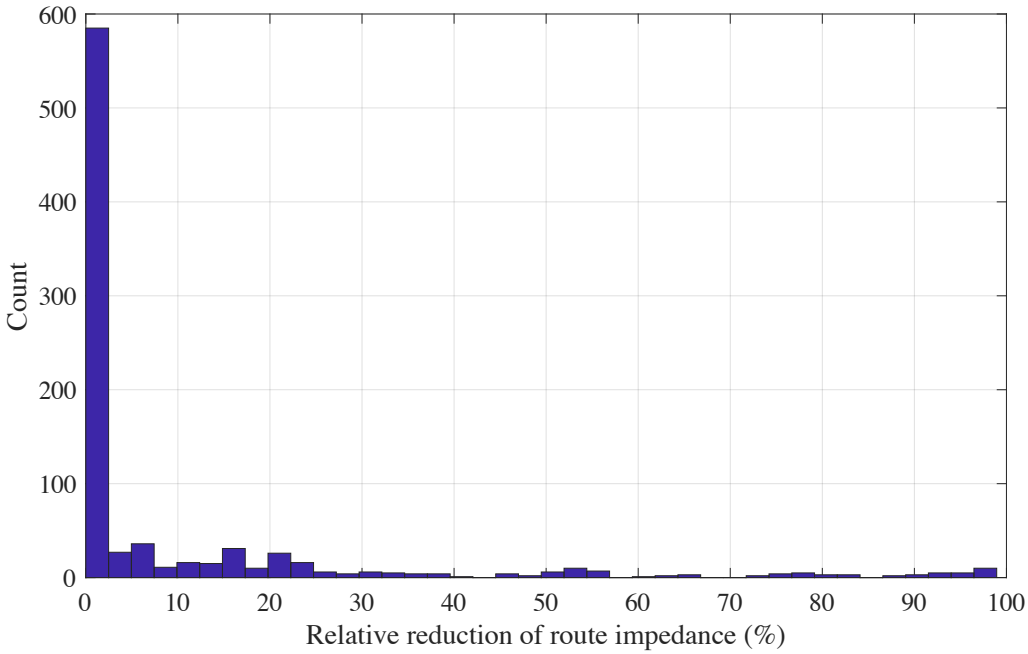

Figure 8.23. Histogram of relative reduction of route impedance for departure aircraft

It can be seen from all three figures that most of the positive impedance reduction is within 20%, with a very long tail that approaches 100% [20]. While for most of the flights, the dynamic route search leads to the default route (indicated as 0% reduction), the proposed algorithm does have some significant impact (with over 20% impedance reduction) on aircraft.

Figure 8.24 shows the reduction of route impedance for all flights by time of the day. It can be seen that while higher reductions exist throughout the day, they are mainly distributed from 9:00 to 22:00, with high concentrations around 10am and 7pm, which are peak periods of the day. The default routes are optimal for most aircraft during 4-6am.

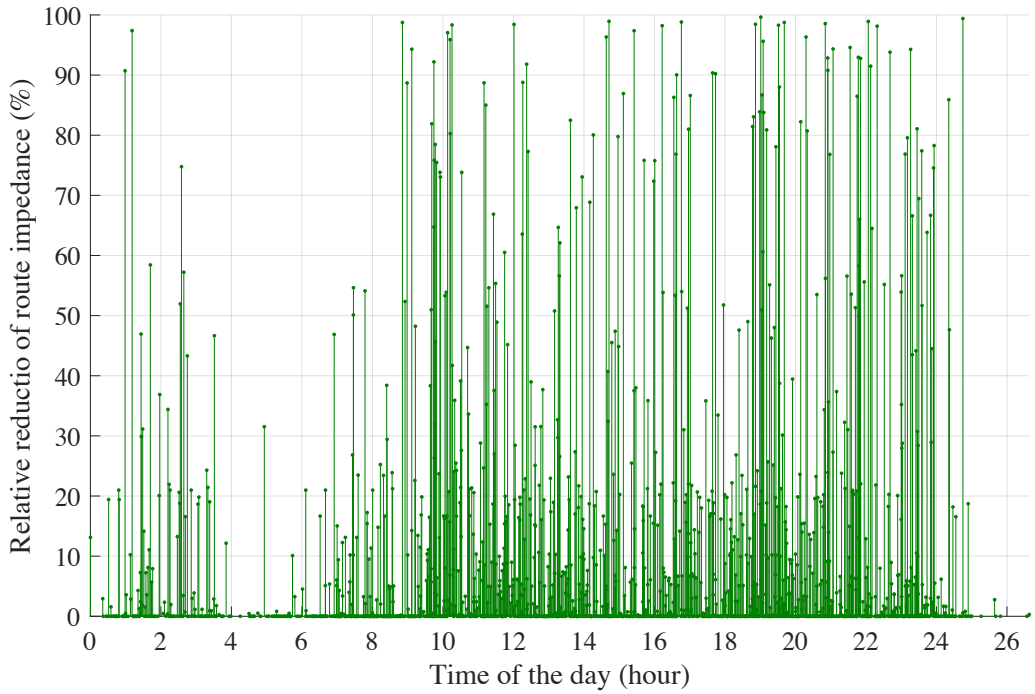

Figure 8.24. Relative reduction of route impedance for all aircraft by time of their entrance into the surface network

[20] According to the definition of route impedance and interaction indicator, avoiding conflicts with other aircraft on the surface could have a considerable impact on the numerical scales of impedance, causing, in some cases, the impedance of different routes to differ by a factor of 10^2 or higher.

Several origin-destination (O-D) pairs and routes used are further checked. In Figure 8.25, the default and alternative routes are shown for two O-D pairs, namely (Apron 4, RWY01) shown in yellow, and (Apron 24, RWY36R) shown in magenta. The reduction of impedance of the optimal route over the default one is shown in Figure 8.26 for (Apron 4, RWY01) and Figure 8.27 for (Apron 24, RWY36R).

It can be seen that for O-D pair (Apron 4, RWY01), the alternative route is predominantly superior to the default one, as most reductions are positive. This is because the default route incurs a major conflict point at the black dot (also see Figure 8.33 for more details), and uses a taxiway that is heavily loaded with other departing aircraft headed for RWY01, and arrival aircraft landed from RWY01.

For O-D pair (Apron 24, RWY36R), Figure 8.27 shows that the default route is more efficient than the alternative one in the afternoon during peak times. This is because the alternative route traverses a conflict point (shown as the black dot, also see Figure 8.34), and uses the taxiway heavily loaded with departing and arrival aircraft.

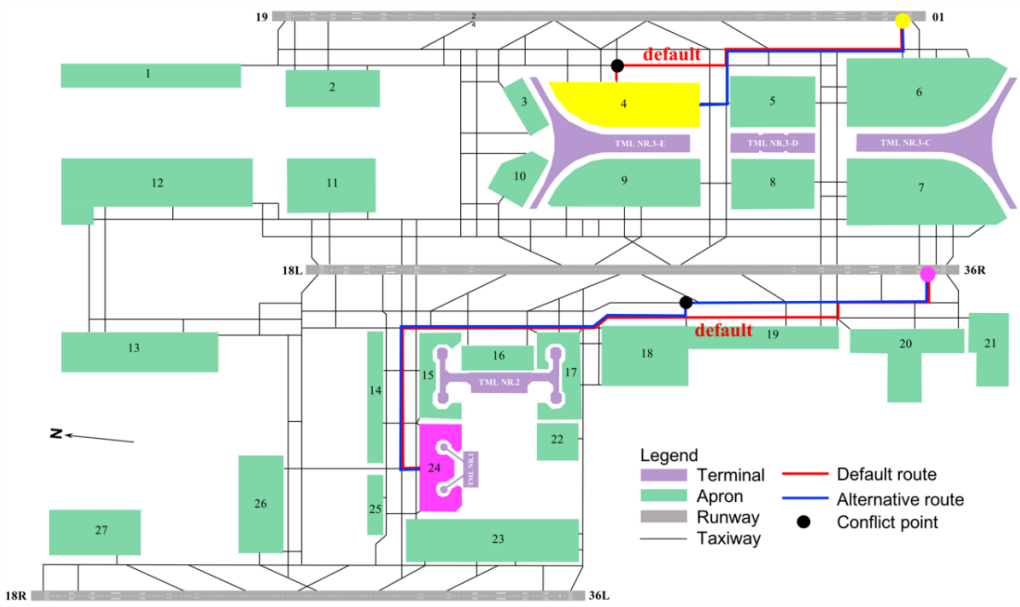

Figure 8.25. Default and alternative routes for two O-D pairs: (Apron 4, RWY01), (Apron 24, RWY36R)

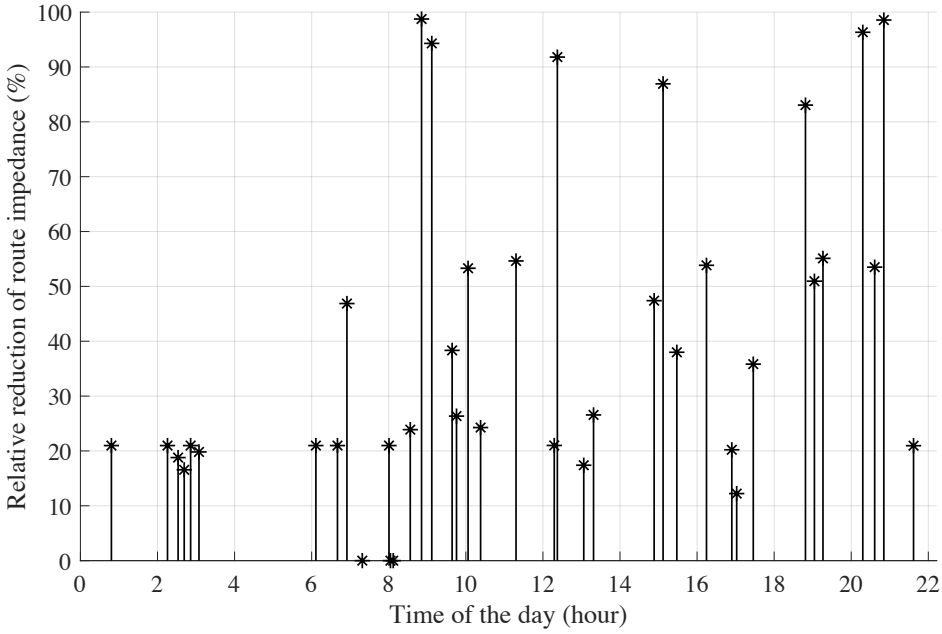

Figure 8.26. Relative reduction of route impedance (over the default route) by dynamic route search for all aircraft between O-D (Apron 4, RWY01)

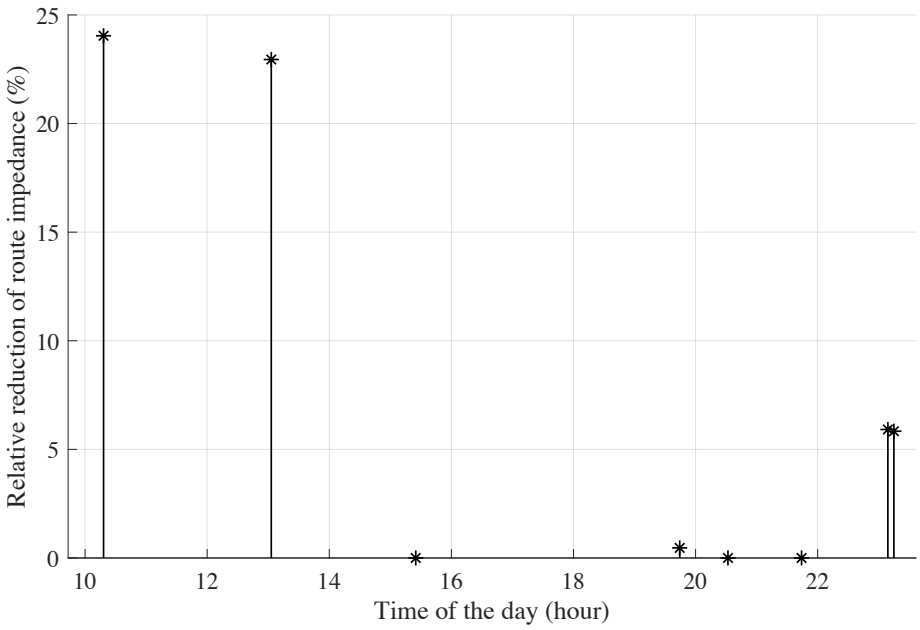

Figure 8.27. Relative reduction of route impedance (over the default route) by dynamic route search for all aircraft between O-D (Apron 24, RWY36R)

In Figure 8.28, two O-D pairs are investigated, (Apron 4, RWY36R) and (Apron 10, RWY36L), each with three admissible routes. As the taxiing distances are longer, the situation becomes more complex. Figure 8.29 shows that the relative optimality between default and alternative routes are constantly switching, indicating the complex nature of the taxiing network dynamics and the need to calculate optimal routes in a real-time fashion. It can be also seen that the route impedance differs greatly from time to time, as the three routes incur four major conflict points (shown as black dot) along the way, also see Figure 8.33. In the case of (Apron 10, RWY36L), the impedance between the default (red) and alternative (blue) is insignificant as they overlap quite considerably; the other alternative (orange) incurs much higher impedance as it traverses several major conflict points along the way.

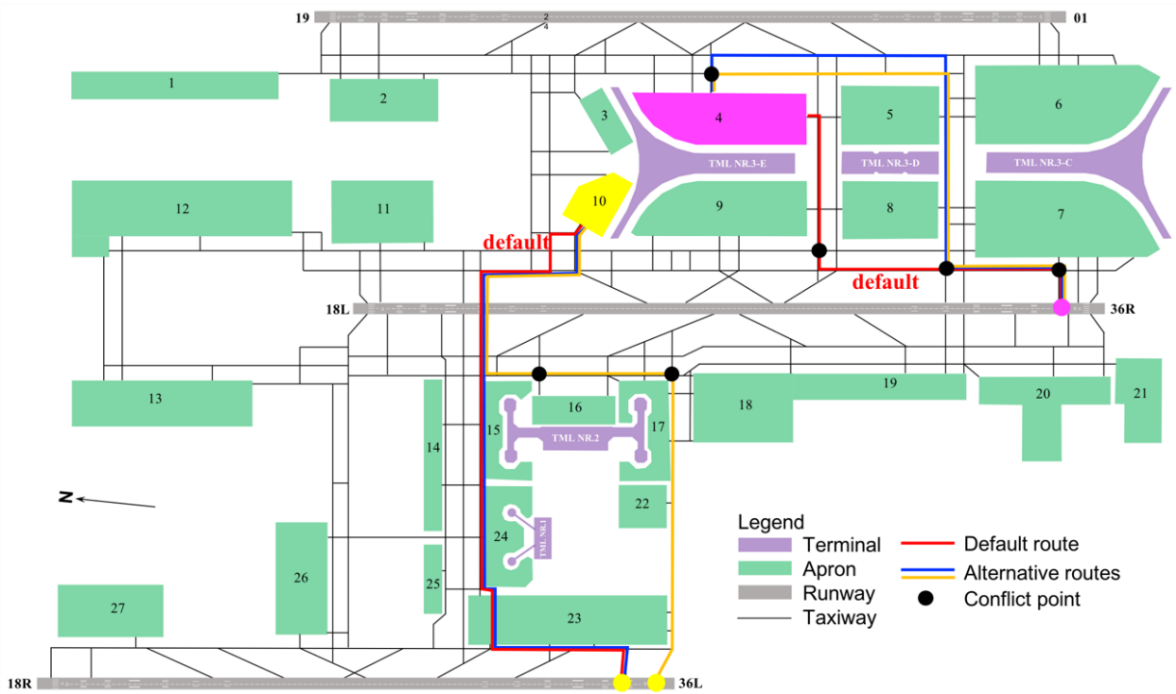

Figure 8.28. Default and alternative routes for two O-D pairs: (Apron 4, RWY36R), (Apron 10, RWY36L)

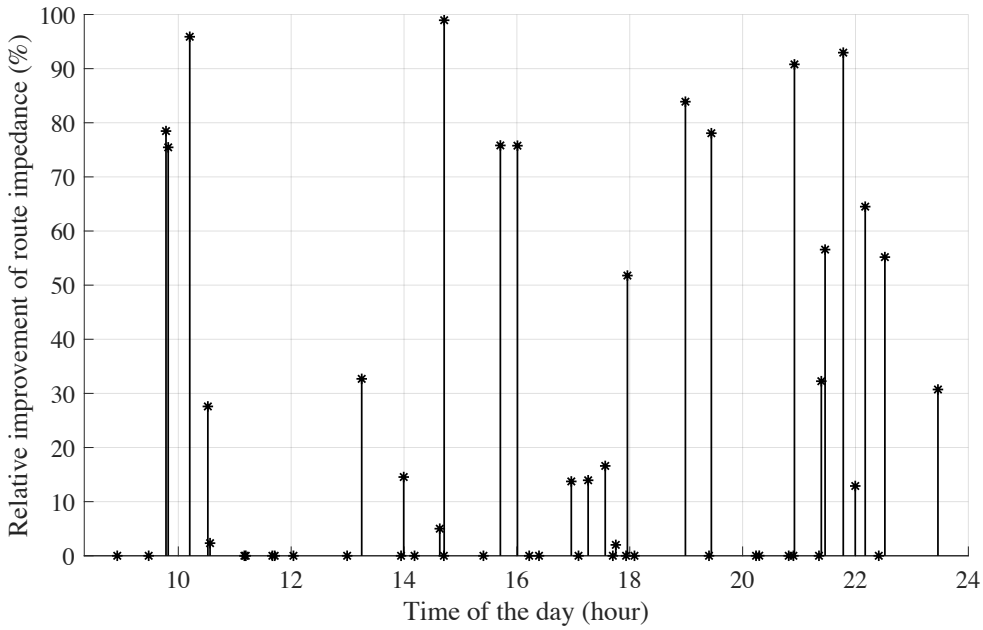

Figure 8.29. Relative reduction of route impedance (over the default route) by dynamic route search for all aircraft between O-D (Apron 4, RWY36R)

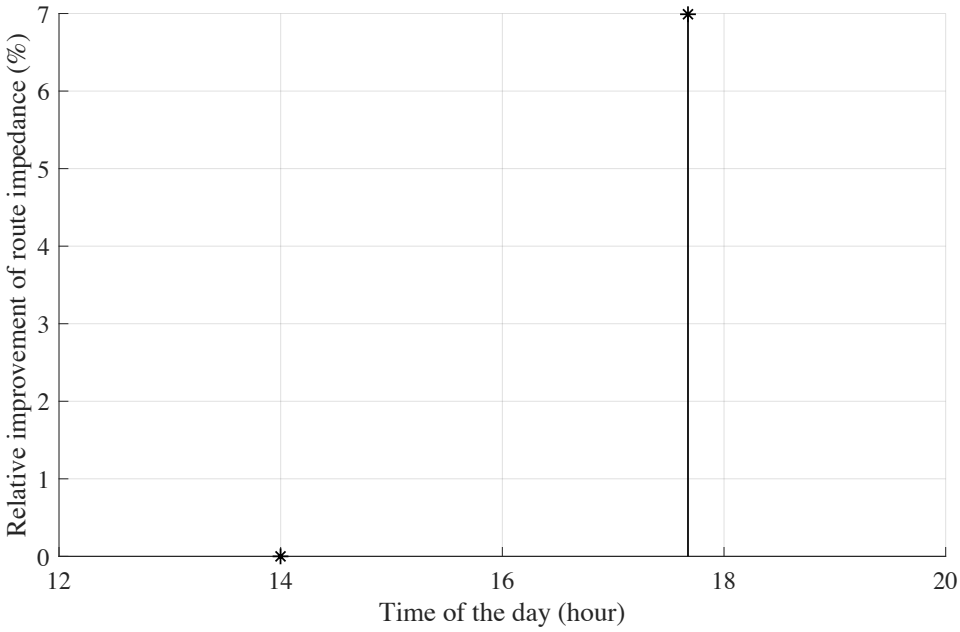

Figure 8.30. Relative reduction of route impedance (over the default route) by dynamic route search for all aircraft between O-D (Apron 10, RWY36L)

8.5.1.3. Taxiing conflicts

The number of conflicts on the entire taxiing network during the 24-hour horizon has decreased from 308 to 255 (by 17.21%), which results from the active route searching that aims to minimise the route impedance, which is derived based on the principle of conflict reduction. Figure 8.31 and Figure 8.32 show the number of conflicts occurring at each of the 313 nodes throughout the 24-hour horizon, which are obtained based on 10 independent simulation runs. It can be seen that a nodal conflict of nearly 50 has been eliminated in the dynamic route search case.

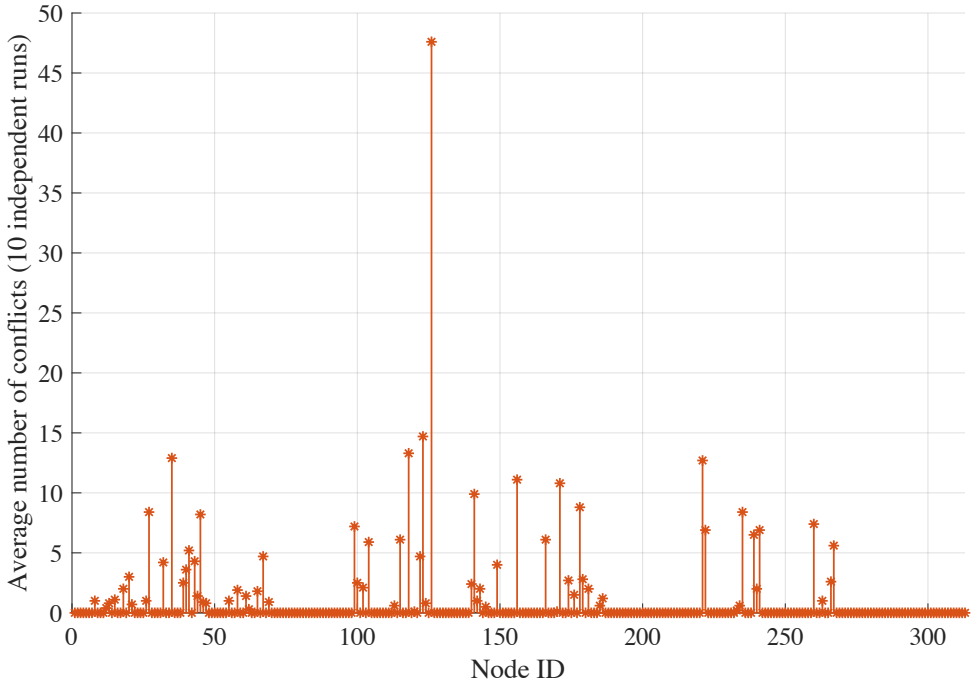

Figure 8.31. Default route choices: Average number of conflicts (over 10 independent simulation runs) at each node

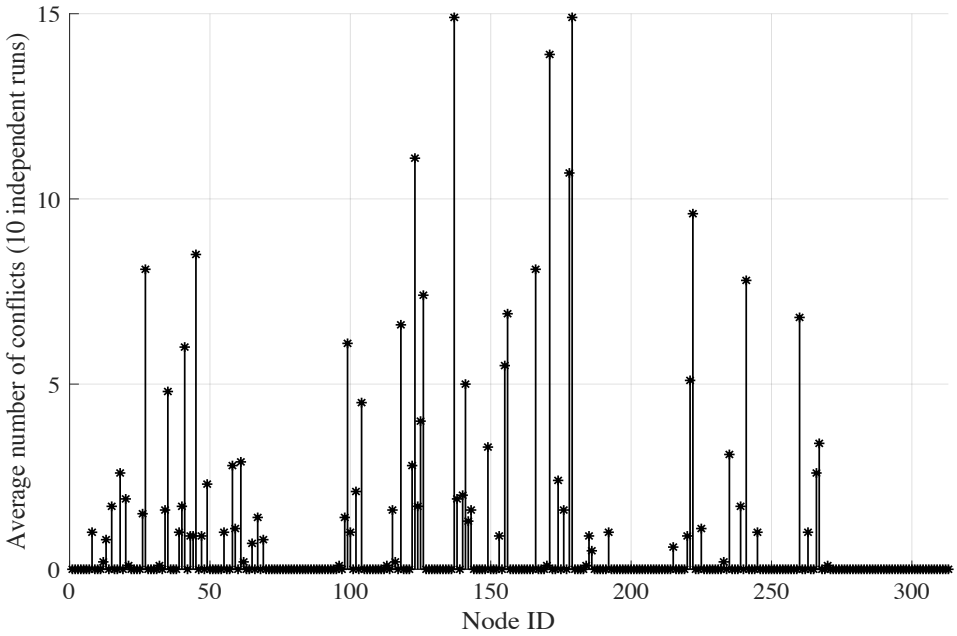

Figure 8.32. Dynamic route search: Average number of conflicts (over 10 independent simulation runs) at each node

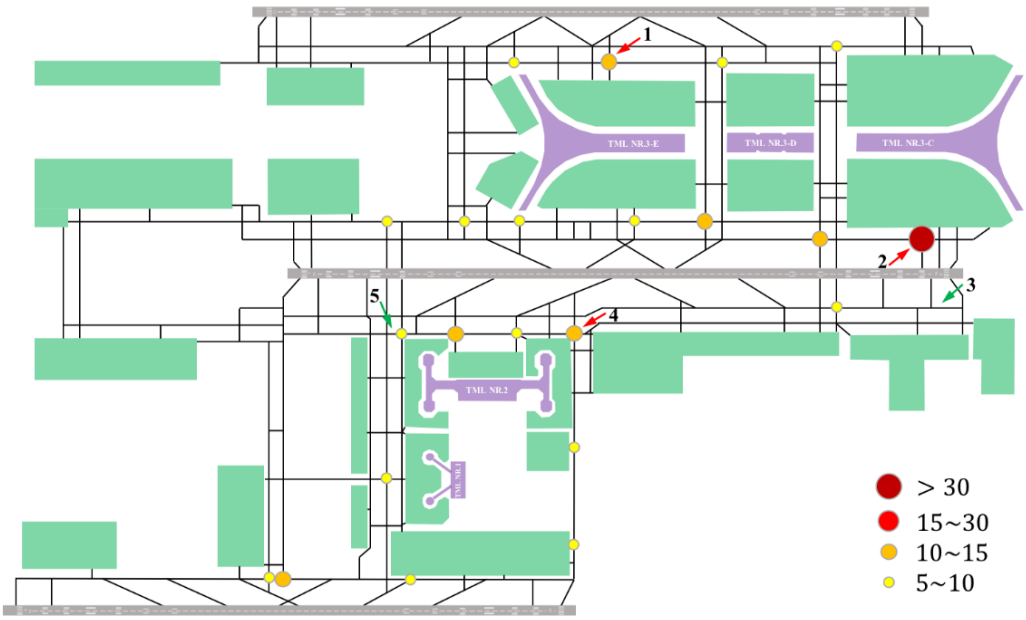

Figure 8.33. Spatial distribution of node conflicts (the numerical scale indicates total number of conflicts occurred during the one-day operational horizon) with default route choices.

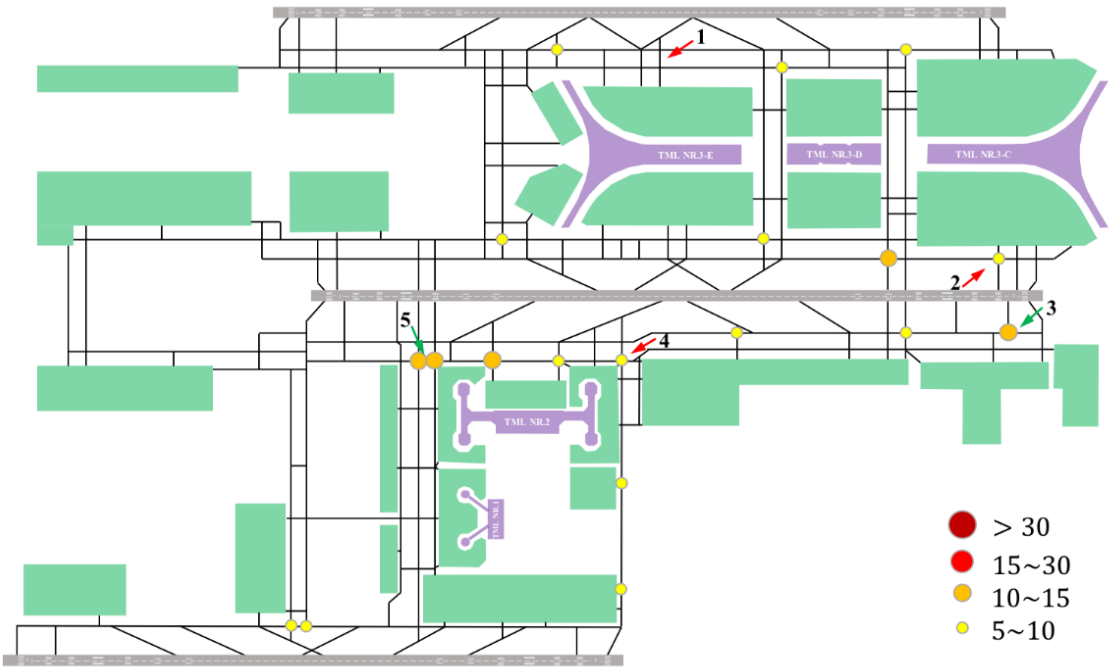

Figure 8.34. Spatial distribution of node conflicts (the numerical scale indicates total number of conflicts occurred during the one-day operational horizon) with the dynamic route search algorithm.

Figure 8.33 and Figure 8.34 compares the spatial distribution of nodal conflicts in the two cases. It can be seen that a major point of conflict (shown as arrow 2) near the runway end of RWY36R has been substantially reduced as a result of re-routing. In addition, the conflict points 1 and 4 are reduced or eliminated. As a trade-off, the conflicts at point 3 and 5 are increased, yet within acceptable range (10~15), which balances the overall spatial distribution of congestion on the surface network.

8.5.2. Integrated Dynamic Routing and Off-block (IDRO) optimisation

In this section, the A-CA simulation results for the integrated dynamic routing and off-block optimisation are investigated. The sets of admissible routes for each O-D pair remain the same as Section 8.5.1. Regarding off-block control, the first-come-first-served approach by

following Algorithm 7 is employed. Relative to the scheduled time of departure, the earliest and latest deviation time is set to be 8 minutes.

As IDRO is only applied to departure aircraft, dynamic route search (Algorithm 5) to arrival flights on the surface network is applied.

8.5.2.1. Overall performance

The same set of KPIs as in Section 8.5.1.1 are used for IDRO. The comparison of taxiing with default route, dynamic route search, and IDRO is shown in

Table 8.12.

Table 8.12. Comparison of default route, dynamic route search, and IDRO.

	Average taxiing time	Average taxiing time for arrivals	Average taxiing time for departures	Average delay	Total conflicts
Default route	15.50 min	11.30 min	19.67 min	29.22 min	308
Dynamic route search	15.35 min	11.25 min	19.44 min	28.93 min	255
IDRO	15.28	11.22	19.32	23.22	210
Improvement over default route	1.42%	0.71%	1.78%	20.53%	31.82%
Improvement over dynamic route search	0.46%	0.27%	0.62%	19.74%	17.65%

8.5.2.2. Reduction of route impedance

The reduction of route impedance for all the departures (as IDRO is only applicable to departures) is summarised as a histogram in Figure 8.35. Note that the reduction is relative to dynamic route search (without the option of choosing different off-block times). It can be seen that with the off-block control, the route impedance can be significantly reduced.

Figure 8.36 shows the reduction of route impedance for all departures by their times of the day. It is seen that the reduction is mainly concentrated from 7am to 24pm.

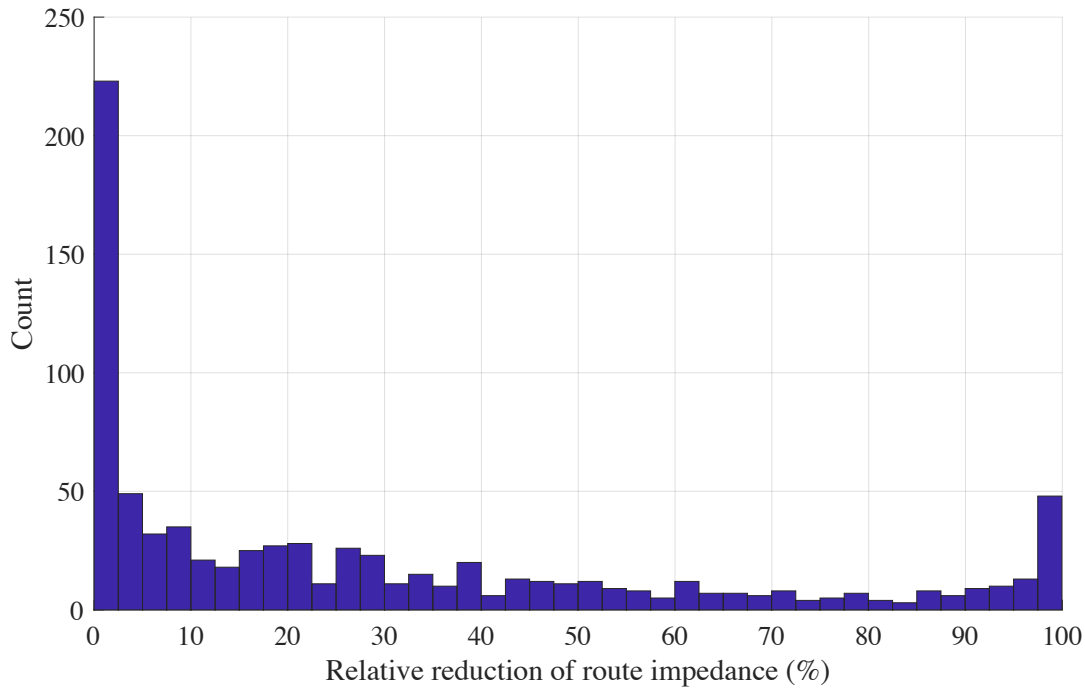

Figure 8.35. Histogram of relative reduction of route impedance for departure aircraft

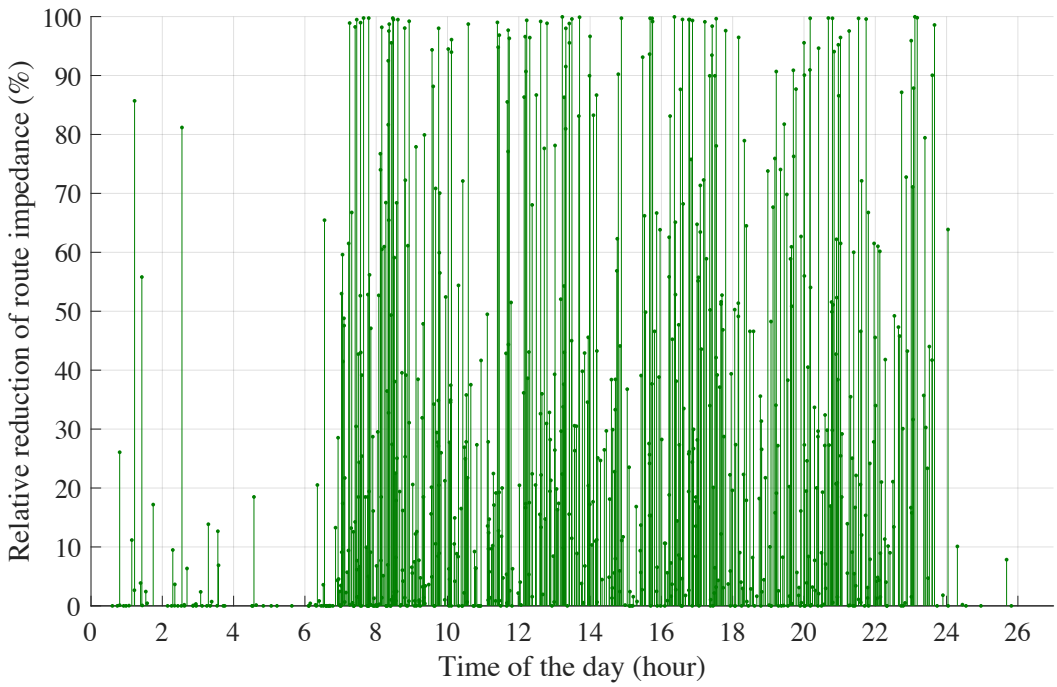

Figure 8.36. Relative reduction of route impedance for all departing aircraft by time of their entrance into the surface network

To further analyse factors that impact the impedance reduction, 10 O-D pairs with the most significant impedance reduction have been found, which is obtained by averaging the impedance reduction of individual flights associated with a given O-D pair. The top 10 O-Ds are shown in Table 8.13. There are two types of O-D pairs that benefit from the proposed IDRO optimisation: (1) those that use main taxi arterials, such as (Apron 19, RWY36R), (Apron 10, RWY36R), (Apron 15, RWY36R), (Apron 5, RWY01), (Apron 20, RWY36R), (Apron 9, RWY36R), and (Apron 18, RWY36R); and (2) those that are far away from the destination, such as (Apron 16, RWY01) and (Apron 4, RWY36R). For the first case, numerous potential conflicts are expected, so having the flexibility of off-block time could considerably reduce route impedance. For the second case, the expected long taxiing distance and time adds more room for off-block time optimisation.

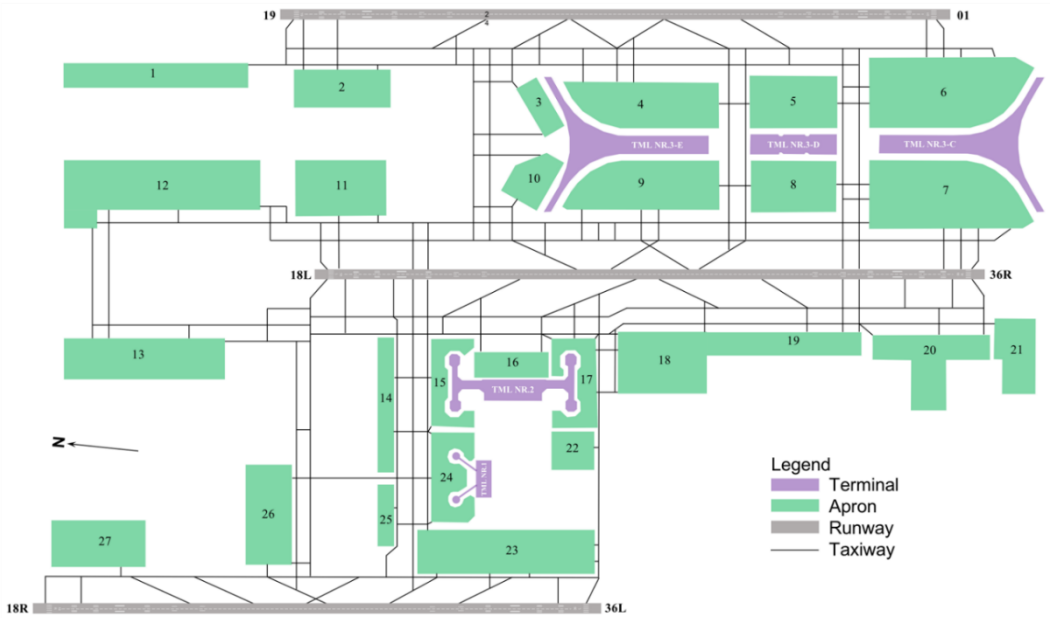

Figure 8.37. Distribution of aprons and runways. For departures, the destinations are RWY01, RWY36R and RWY 36L.

Table 8.13. Top 10 O-Ds with the most average impedance reduction.

Number	Origin	Destination	Average impedance reduction	No. of departing flights
1	Apron 19	RWY36R	37.3%	19
2	Apron 16	RWY01	26.0%	5
3	Apron 10	RWY36R	24.1%	15
4	Apron 15	RWY36R	19.9%	43
5	Apron 5	RWY01	19.2%	13
6	Apron 20	RWY36R	19.0%	21
7	Apron 9	RWY36R	18.7%	24
8	Apron 18	RWY36R	18.6%	31
9	Apron 4	RWY36R	17.0%	51
10	Apron 4	RWY01	16.8%	39

8.5.2.3. Taxiing conflicts

The nodal conflicts in the dynamic route search and IDRO cases are shown in Figure 8.38 and Figure 8.40, respectively. It can be seen that the IDRO further reduces nodal conflicts, especially for those with significant conflicts.

In Figure 8.41 and Figure 8.42, the spatial distribution of the conflicts is further compared. With the proposed IDRO, the conflicts near the eastern side of RWY36R (arrows 1 and 2) are reduced, and those conflict points along the taxiway west of RWY36R (arrow 3) are eliminated. This is consistent with the observations made regarding Table 8.13.

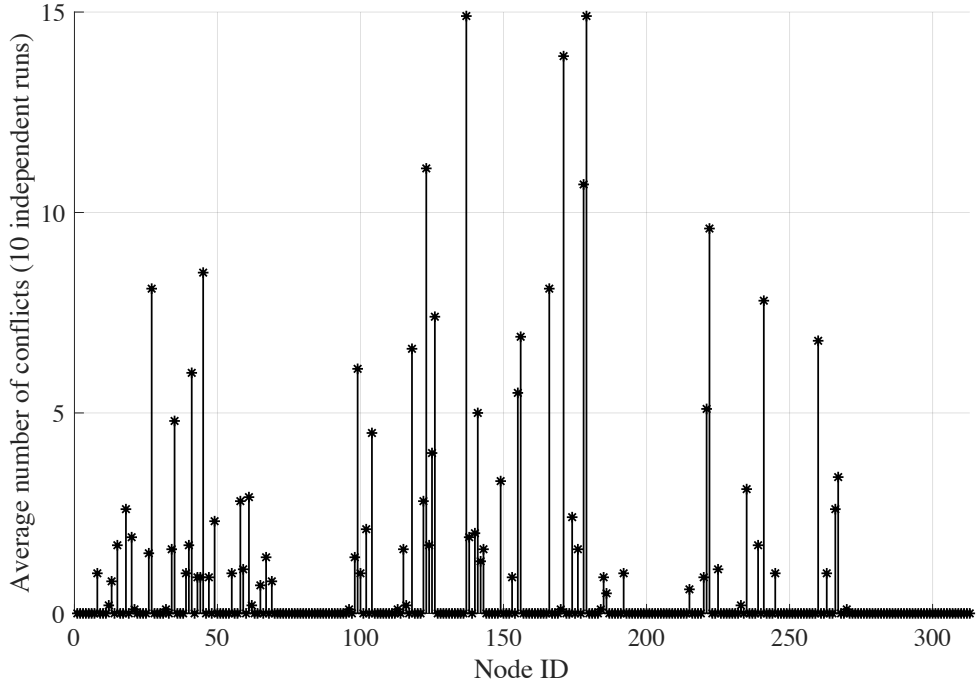

Figure 8.38. Dynamic route search: Average number of conflicts (over 10 independent simulation runs) at each node

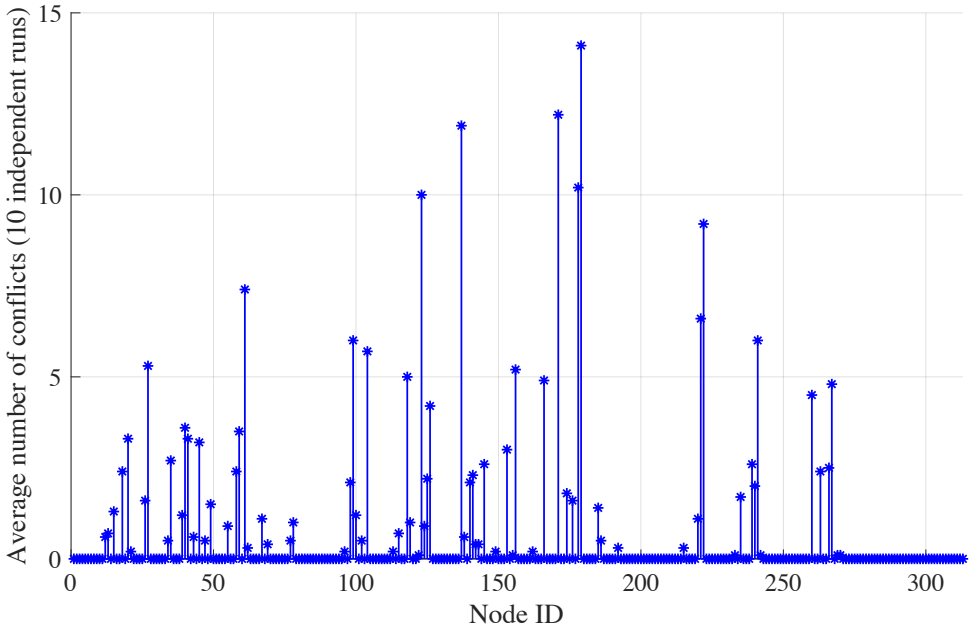

Figure 8.39. Integrated dynamic route and off-block optimisation: Average number of conflicts (over 10 independent simulation runs) at each node

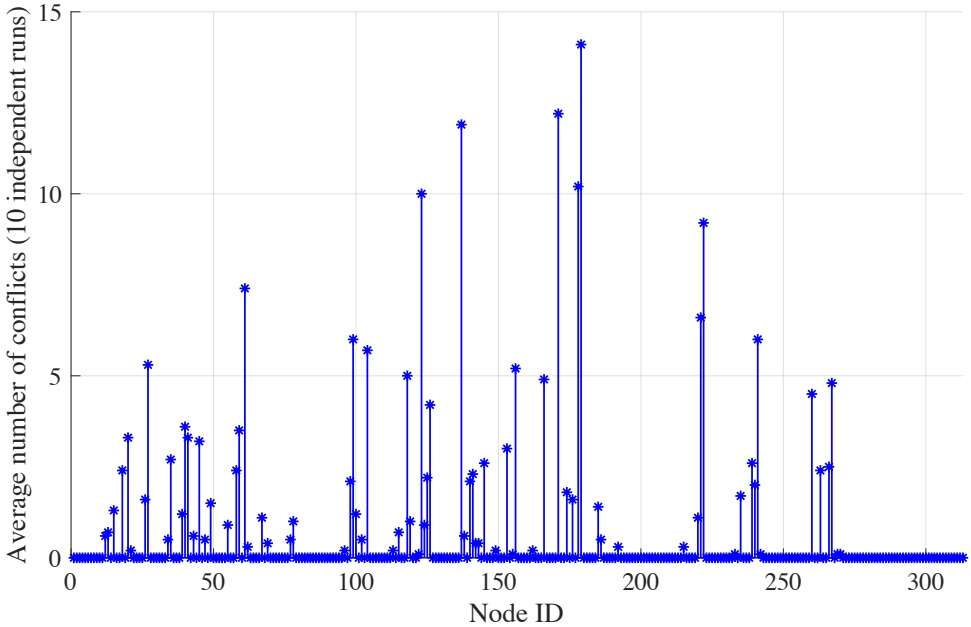

Figure 8.40. Integrated dynamic route and off-block optimisation: Average number of conflicts (over 10 independent simulation runs) at each node

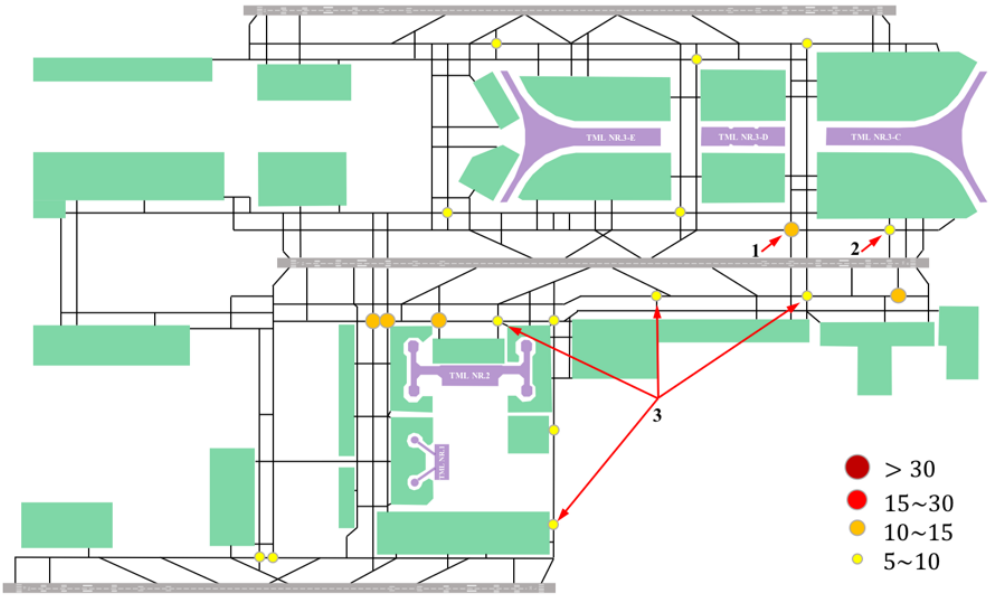

Figure 8.41. Spatial distribution of node conflicts (the numerical scale indicates total number of conflicts occurred during the one-day operational horizon) with the dynamic route search algorithm.

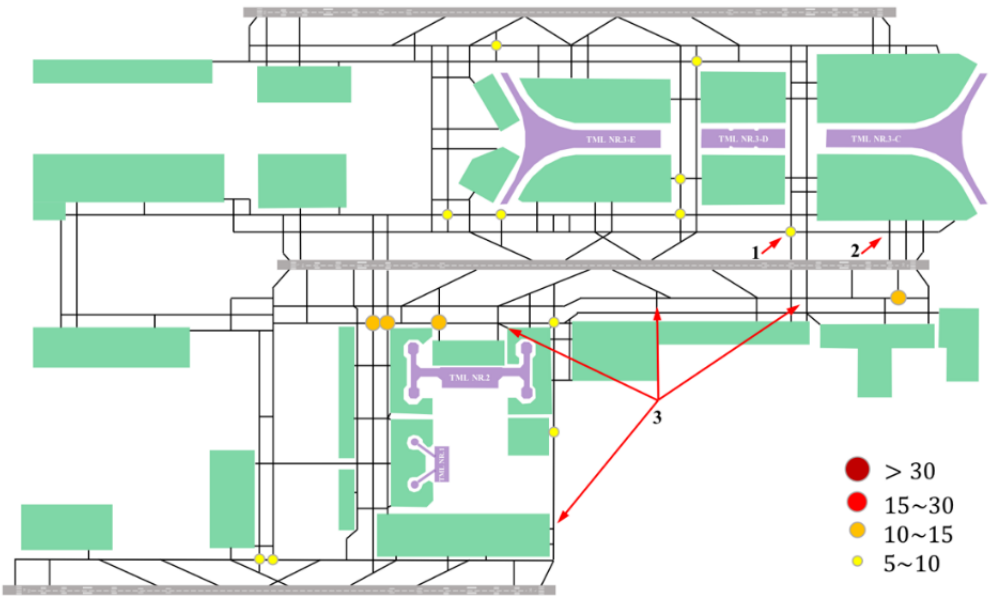

Figure 8.42. Spatial distribution of node conflicts (the numerical scale indicates total number of conflicts occurred during the one-day operational horizon) with the integrated dynamic routing and off-block optimisation.

8.6. Joint IARA-IDRO

In this section, the quantitative validation of the proposed the joint of integrated apron and runway assignment, and integrated Dynamic Routing and Off-block optimisation (IARA-IDRO) is investigated. This is to be achieved by comparing the A-CA simulation results for the proposed optimisation (*Test Case*) with that for the current operation (*Base Case*). In terms of the *Base Case,* the O-D pair and taxiing route are set according to the history data and standard taxiing route, while for the *Test Case,* the proposed algorithms 1 to 5 have been applied to the flight demands on the simulated day (14th Sep 2017), by considering the operation rules, constraints, preferences of the runway, apron, and taxiway assignments.

The ACA simulation is performed with over 10 independent simulation runs for both current operation (Base Case) and new proposed joint IARA-IDRO (*Test Case*), with results summarised and compared in Table 8.14. It can be seen that all five KPIs are improved when using the joint IARA-IDRO algorithm proposed in this work. In terms of taxiing time reduction, the level of improvement, although considerable, is lower than that for distance reduction (see Table 6.6), and runway queuing reduction as well as conflicts (see Table 8.14). This is because the O-D re-assignment mainly focuses on the taxiing distance reduction for flight demands, and the way route impedance is defined mainly focuses on congestion and taxiing conflicts, rather than taxiing time, although they are obviously related. When the network is near-saturated (which is the case for PEK), the room for shortening taxiing time is limited as the main bottleneck is runway queuing, which cannot be directly addressed by routing strategies. Table 8.14 shows a considerable reduction of total conflicts, as is expected from both O-D re-assignment with the main objective of reducing the taxiing crossing (i.e. from the east to the west, or vice versa) on the surface, as well as from the definition of route impedance and the impedance-based routing strategy.

In terms of runway queuing, due to both the congestion-aware runway assignment procedure aiming at balancing the utilisation of all three runways and off-block optimisation within the apron that release the aircraft at the appropriate time, the mean queuing time and maximum

number of queuing flights have decreased significantly. In particular, RWY01, which has the highest throughput during daytime operation, has experienced a drastic reduction of congestion after the new proposed joint IARA-IDRO (by 56.9% and 58.7% for queue length and queuing time, respectively).

Table 8.14. Key performance indicators from ACA simulation based on the current and new proposed integrated and joint optimisation research

KPIs		Current assignment	Proposed joint IARA-IDRO	Improvement (%)
Average taxiing time (incl. queuing, apron delays) (min)	**Combined**	16.5	15.28	7.4
	Arrival	11.8	11.22	4.9
	Departure	21.3	19.32	9.3
Average Flight Delay (min)		30.32	23.22	23.4
Runway queuing [RWY01, RWY36R, RWY36L]	**Longest queue (# of aircraft)**	[7.2, 6.6, 4.2]	[3.1, 4.9, 4]	[56.9, 25.8, 4.8]
	Mean queuing time (min)	[4.6, 1.7, 2.5]	[1.9,1.1,2.1]	[58.7, 35.3, 16]
Total number of conflicts		382.6	210	45.1

8.7. DISCUSSION

The quantitative results based on A-CA model shown in Section 8.6, along with the qualitative validation by SEMs introduced in Section 8.1.3, have provided a proof of the joint IARA-IDRO concept and shown positive potentials in operation performance. This is illustrated in main KPAs as follows.

1) Capacity

As the definition of the capacity is that the maximum number of aircraft that could be serviced during a certain time period within a specific airport. The value of operation capacity is determined under a certain degree of delay, such as 15 min or 30 min. The proposed framework can improve operational efficiency, which is positive to the improvement of capacity.

2) Operational efficiency

The proposed joint IARA-IDOR framework enables the optimal use of available capacity through integrated optimisation of runways, taxiways and aprons on the surface, thereby reducing taxiing distance, conflicts, runway queuing time, taxiing delays.

3) Environmental impacts

As aforementioned, the number of acceleration and deceleration events are positively correlated to fuel consumption and emissions, and that has been studied in Khadilkar and Balakrishnan (2012). In this research, the significant reduction in the number of conflicts under the proposed framework can make the aircraft moving smoothly with reduced braking events caused by excessive congestion and the number of speed-up after conflict resolution on the airport surface, hence, to reduce the environment pollution.

4) Safety

Previous research has indicated that the workload of ATCOs is highly related to the safety of the operation, and prolonged working time would result in worse performance. Normally, the role of the ATCOs is to monitor the aircraft activities, to issue command to resolve potential conflicts, and to guide the aircraft taxiing, take-off, and landing. The proposed IARA-IDOR shows a significant reduction in the number of conflicts, which not only enhances the safety of operation on the airport surface, but also contribute to a reduction of ATCOs' workload as fewer number of interferences are required.

5) Cost-efficiency

Unlike the previous work focusing on the reduction of taxi time with engine-on to reduce fuel burn and emissions (Balakrishnan and Jung, 2007; Roling and Visser, 2008; Gotteland et al., 2001), the consequence of the reduction of taxiing distance for each aircraft due to resulting integrated assignment has been considered, thereby reducing taxiing time. In particular, the proposed IARA-IDOR has shown that a significant reduction in the number of conflicts that contribute to a more stable taxiing process.

8.8. SUMMARY

This chapter has performed a comprehensive validation process for the proposed joint IARA and IDRO optimisation procedures. A series of KPIs have been defined that are used for quantitative assessment, and A-CA model has been set up and calibrated using empirical data from PEK. The A-CA is also used alongside the dynamic route search and off-block algorithms to generate routes and off-block times within simulations, which reflects the real-time operational features of these algorithms. Compared to the current operations, the proposed IARA-IDRO algorithm is promising, with reductions in total taxiing distance, average taxiing time, taxiing conflicts, and runway queuing. Furthermore, a series of quantitative validation is conducted based on interviews with SMEs, in order to gain insights into the operational feasibility of the proposed joint optimisation, and its potential for field implementation.

In Chapter 9, in addition to research output and findings, a discussion of the potential for implementation of the proposed concept and methodology is performed.

CHAPTER 9 RECOMMENDATIONS FOR IMPLEMENTATION

9.1. RESEARCH OUTPUT AND FINDINGS

This research investigates the concept of joint operations of individual airport components, in particular runways, taxiways, and aprons. A joint apron-runway assignment and dynamic routing and off-block optimisation framework is proposed aiming to improve airport surface operations in terms of taxiing efficiency, delay, runway throughput, and conflicts. In this process, the runway and apron assignment rules as well as taxiing rules pertaining to PEK operations are fully considered and reflected in the proposed solutions. The effectiveness of the integrated optimisation is demonstrated in the PEK case study, where an airport cellular automata model is developed to simulate the detailed surface movement of aircraft.

The following findings are obtained from the quantitative assessment at PEK:

1. By actively assigning runways and aprons to each aircraft, the total taxiing distance and percentage of gate assignments can be significantly improved, by 15.5% and 11.8%, respectively (see Table 6.5 and Table 6.6). These benefits are directly accounted for in the IARA procedure as prioritised objectives of optimisation.
2. In IARA, stand reservation period is extended to accommodate schedule uncertainties for arrivals and departures. As uncertainties increase, the number of gate assignments reduces as stand utilisation becomes lower. On the other hand, the total taxiing distance slightly decreases as well, due to the fact that some flights are assigned to remote stands that are closer to the runways (see Table 6.5).
3. The IARA also brings improvement to runway queuing, by significantly reducing longest queue and mean queuing time, especially for RWY01 (see Table 8.9). This is attributed to the congestion-aware runway assignment (Section 5.6.2).

4. According to the A-CA simulation results (Table 8.9), the IARA reduces average taxiing time by 3.7% for arrivals and 7.7% for departures. The larger improvement for departures is possibly due to the congestion-aware runway assignment, whereas for arrivals their designated runways are fixed. Moreover, in the new runway-apron assignment, the taxiing conflicts are reduced by 19.8%, partly due to runway queuing mitigation and elimination of long-distance taxiing routes.
5. The proposed dynamic routing strategy tends to reduce route impedance for about 38% of the total flights (Section Figure 8.21). Although the notion of route impedance is only an artefact intended as an objective of real-time route optimisation, the A-CA simulation suggests that the proposed routes yield significant reduction of taxiing conflicts, by 17.21%. In addition, the average taxiing time slightly reduces by 0.97%, and average delay (actual time minus scheduled time) reduces by 0.99% (Table 8.11).
6. When combining dynamic routing with off-block control (IDRO), about 74% of departing aircraft are assigned routes with lower impedance than their default one. Compared with route search only, IDRO further reduces the taxiing conflict by 17.65%, taxiing time by 0.46%, average delay by 19.74% (
7. Table 8.12). In can be concluded that the proposed off-block control has most significant impact on taxiing conflict and average delay, as it is able to allow departing aircraft to be off-blocked as early as possible subject to route impedance minimization.
8. Comparing IDRO with default route and off-block times, the former is able to reduce average taxiing time by 1.42%, average delay by 20.53%, and total conflicts by 31.82% (
9. Table 8.12), which shows high potential of IDRO for mitigating taxiway conflicts and taxiing delays.
10. The integrated IARA-IDRO optimisation, when compared to the default runway and apron assignment as well as off-block times and taxiing routes, yields the following improvement: average taxiing time by 7.4%, average delay by 23.4%, runway queuing time by [58.7%, 35.3%, 16%] (RWY01, RWY36R, RWY36L), total taxiing conflicts by 45.1%.

This proposed IARA-IDRO is performed by considering runway and apron assignment rules, constraints and preferences, taxiway and TMA rules and constraints. These rules, constraints, and preferences, although differ in detail, are broadly similar in all Chinese airports. Therefore, using the proposed methodology with minor adaptation (such as generation of priorities over flights, aprons, and runways), one can come up with similar priority-based apron and runway assignment, as well as route search and off-block control strategies.

For airports in the USA or Europe, a similar priority-based structure for flights can be adopted (Sidiropoulos, 2016). Regarding runway and apron assignment rules, attention should be given to the integration with current airport surface management tools (Section 3.1). The required data and airport information for the implementation of the proposed framework are summarised in Table 9.1.

Table 9.1. Required data and airport information

Framework	Data required	Airport information
IARA	• Flight time (i.e. STD, STA, ATD, ATA, AIBT, AOBT; CTOT/TTOT); • Flight type (i.e. departure or arrival, domestic or international; passenger or cargo); • Aircraft category (i.e. SH, H, M, L); • Flight information; • Apron and runway information for each flight; • Aircraft registration number; • Weather condition (i.e. runway operation mode); • Six-month and more historical data (includes above flight information).	• Airport Network topology and detailed information • Apron and runway parameters; • Conflict resolution rules; • Apron and runway operation rules, constraints and preferences. • Airlines distribution in terminals and their preferences; • Minimum Turn-around Time; • Runway operation mode.
IDRO	• Flight time (i.e. ELDT, EIBT, CTOT, TTOT, TOBT, COBT); • Flight type (i.e. departure or arrival, domestic or international); • Apron-runway information for each flight demand; • Admissible routes for each flight (according to the taxiing rules of the airport & SMEs interviews).	• Airport Network topology and detailed information; • Taxiing speed limitations (e.g. on straight taxiways, turning points, aprons, runways); • Taxiing rules and constraints; • Minimum Turn-around Time.

9.2. IMPLEMENTATION CONSIDERATION

1. The proposed apron-runway assignment framework is conceived in a strategic or pre-tactical operational environment, where detailed flight schedules are an input. In real-world operations, schedule uncertainties are partly handled by the proposed robust approach. However, extreme events such as flight cancelations and adverse weather could bring significant changes. To address this, the optimisation framework can be modified by taking near real-time flight information (e.g., 2hours in advance) as input, and performing lexicographic optimisation following a rolling horizon approach.

2. Operational protocols and contingencies that are more likely to be specific to individual airports or regions (e.g., different assignment constraints or flight rankings) can be similarly adopted in the lexicographic apron-runway assignment and the routing and off-block control framework. To operationalize the findings of this work, the following actions are recommended:

- Review airport operational protocols to express taxiing and assignment rules in terms of key constraints that must be obeyed, as well as preferences to be incorporated;

- Identify and characterise the main source of uncertainties in surface operations, which would inform the modelling and optimisation procedure;

- Review data sources and map them to the model input. Depending on the data availability and quality, adjust the modelling and optimisation details to deliver expected outputs.

3. Although this work assumes the existence of airport configurations and established operational rules, it could be used to undertake a what-if analysis that informs the planning and design of airport surface layouts, including taxiway/apron/runway intersections and the distribution of stands. For example, one could use the assignment framework alongside other qualitative considerations to determine the optimal apron layouts and stand allocations. One

could also use the simulation results to identify conflict hotspots and main areas of congestion to consider in the design of network layouts and taxiing routes.

4. Taxiing conflicts contribute to a significant portion of risk and the ATCO's workload. One of the ATCO's duties is to monitor the aircraft activities on taxiways and transitional areas or intersections, issue commands to resolve potential conflicts, and guide the aircraft while taxiing. Previous research indicates that the workload of ATCOs is highly related to the safety of the operation, and prolonged working time could result in worse performance. Therefore, safety regulators could use this research to not only identify conflict zones but also reconfigure the trip distribution on the surface to reduce the level of expected conflicts, thereby reducing the potential risks and the ATCOs' workload, leading to improved safety performance at the airport.

9.3. SUMMARY

The detailed research output and findings have been drawn in this chapter followed by providing potential implementation of the proposed concept and methodology for industrial and academic practice, based on the qualitative and quantitative assessments of the results.

Chapter 10 draws conclusions from the thesis, and identifies the limitations and potential extensions for future work.

CHAPTER 10 CONCLUSION AND FUTURE WORK

This chapter draws conclusions from the work presented so far in this thesis, including a comprehensive review of the levels of completion for each research objective (see Section 10.1), and a mixed-methods approach summary (see Section 10.2). It also concludes this research by identifying caveats and guidelines for future work (see Section 10.3).

10.1 COMPLETION OF RESEARCH OBJECTIVES

The research objectives set out in Section 1.2 are recapped below, followed by the level of completion achieved by the research work.

- **Objective 1.** Review relevant literature to gain a critical understanding of (a) research methodology related to the optimisation of airport operations; (b) the main hurdles to airport capacity expansion and operational improvement from methodological and regulatory perspectives; and (c) administrative and technological constraints for the proposed integrated apron-taxiway-runway optimisation.

  Level of completion. Objective 1 has been completed as presented in Chapters 2 and 3. In particular, (a) was completed with a comprehensive review of methodologies adopted in the existing literature on the optimisation of airport operations (Section 3.2), in particular, quantitative and qualitative methods, as well as the mixed- methods adopted in current research were reviewed (see Section 3.2.2); (b) was finished with a review of existing airport surface management initiatives in SESAR and NextGen (Section 3.1); (c) was accomplished using a qualitative approach (including interviews with SMEs and site visits)
- **Objective 2.** Set up and calibrate a microscopic simulation model for airport surface movement based on the Cellular Automata model for Airport surface (A-CA). This calibrated model serves as the main simulation platform for validating the proposed optimisation solutions and comparing them with existing operational conditions, by computing relevant Key Performance Indicators (KPIs). To validate the model, its input parameters and simulation outputs under various scenarios were checked by the SMEs

from PEK AOC. The A-CA is also embedded in the dynamic route search and off-block algorithms to dynamically generate routes and off-block times, by simulating the real-time operational environment.

Level of completion. The completion of Objective 2 has been discussed in Section 4.3, where the A-CA model components are introduced in detail, and later in Section 8.3, where the A-CA model is further developed in accordance with the specification of PEK. The developed A-CA model is validated against empirical data from PEK (Beijing Capital International Airport), which spans two days and involves over 3000 flights. The errors (RMSE) in taxiing time estimation are within 0.70 min for arrivals and within 0.13 min for departures; the corresponding relative errors (SMAPE) are within 5.1% for arrivals and 0.59% for departures; the relative errors (SMAPE) for runway throughput are within 0.86% (see Table 8.7 and

Table 8.8). In addition, the details of the simulation, the calibration results and the simulation output are reviewed by SMEs in the third round of interviews (see Section 8.1.3). Thus, it is concluded that the developed A-CA model for PEK can reasonably capture the dynamics on the surface network and produce KPIs that agree with empirical data for the baseline scenario.

- **Objective 3.** Perform integrated apron-runway (origin-destination) assignment (IARA) on a pre-tactical level, while considering airport operational constraints as well as runway and apron assignment rules and preferences.

  Level of completion. Objective 3 has been accomplished, as discussed in Chapter 5, This was achieved with a mixed qualitative-quantitative approach, where apron and runway assignment rules and constraints, as well as the cluster ranking were first obtained from interviews with SMEs (Section 5.4) and a questionnaire survey (Section 5.5), respectively, serving as the guidance for design optimisation procedures that are quantitative in nature (Section 5.6). This framework was further implemented and tested later as described in Section 8.4, which has demonstrated its effectiveness in improving airport surface operations on a pre-tactical level, with different levels of uncertainty involving flight schedules.

- **Objective 4.** Building on the IARA solution in Objective 3, develop dynamic route search and integrated dynamic routing and off-block (IDRO) optimisation algorithms in a real-time decision environment, with empirical data and operational rules as inputs.

  Level of completion. Objective 4 has been completed, as presented in Chapter 7, where the real-time dynamic routing and off-block control algorithms are developed based on the novel concept of dynamic route impedance. The IDRO method was tested in the PEK case study based on the A-CA simulation. The results show that it has significant potential to reduce taxiing conflicts and taxiing delays.
- **Objective 5.** Validate and assess the operational feasibility and effectiveness of the proposed joint IARA-IDRO optimisation framework, based on a case study in Beijing Capital International Airport (PEK) using real-world data. The validation test concerns both quantitative assessment in terms of a range of KPIs, and qualitative assessment of its operational viability and potential for field implementation.

  Level of completion. Objective 5 has been accomplished, as discussed in Chapter 8, where the proposed joint IARA-IDRO optimisation framework has been thoroughly evaluated based on a number of KPIs (A-CA simulation). The results are quite promising. In addition, the operational feasibility of the proposed measures has been assessed and confirmed by interviews with subject matter experts from PEK (see Section 8.1.3).
- **Objective 6.** Based on the qualitative and quantitative assessments of the results, make recommendations for industrial and academic practice. In particular, consider how the proposed research framework and outcome can be adopted and adjusted to deal with real-world operational environment and operational diversities across different geographical locations, and how the planning and design of airports can be informed by the research outcome to improve their efficiency and safety performances (Chapter 9).

  Level of completion. Research outcomes and main findings are summarised in Section 9.1, where the proposed framework of IARA, DRS and IDRO are respectively investigated. Moreover, based on the results of the proposed work, different aspects of implementation have been considered (Section 9.2)

10.2 QUALITATIVE AND QUANTITATIVE ASSESSMENTS

In this thesis, a mixed methodology, considering both qualitative and quantitative methods have been adopted. The mixed methodology not only ensures that the modelling and optimisation of airport surface traffic are properly informed by the operational rules of the airport and the user preferences of key stakeholders, but also generates test scenarios and quantitative results that can be assessed by SMEs in terms of the operational feasibility of the proposed designs and their potential impact on airport operations.

In an initial stage, the first round of interviews (see Sections 5.4.2) provided the author with not only a deep understanding of current surface operational characteristics, but also operation-related documents from airports including qualitative data (i.e. rules, constraints and preferences that should be considered while performing runway and apron assignments) (Section 5.4) and quantitative data (i.e. one-year real-world operational data) as well as airport information (see Section 6.2) that are used later in the mathematical optimisation model (Section 5.6 & Section7.2 & Section7.3) and the simulation model (Section 8.3). In the process of the research, a second round of questionnaire surveys (Section 5.5) was performed to determine the priority ranking of the 20 clusters to be considered in the mathematical optimisation model (Section 5.6). The third round of interviews was conducted to validate the effectiveness of the proposed integrated work and to provide recommendations for the potential applications and implementation in the future (Section 8.1.3).

10.3 FUTURE RESEARCH DIRECTIONS

This research may be extended in the following directions.

- The runway assignment procedure considers only one operational mode throughout the day. Different runway operational modes, which might change dynamically throughout the day, can be easily accommodated by refining the feasible runway sets for each aircraft.
- In this research, the runway assigned for arriving flights is treated exogenously. In future work, the proposed apron-runway assignment can be extended to interface with TMA operations, thereby broadening the impact of the integrated airport operation.
- Although conceived in a pre-tactical decision environment, the overall apron-runway assignment framework can be adapted to treat real-time operations following a similar lexicographic design.
- The current dynamic route search algorithm uses free-flow taxiing time as an approximation, which can be replaced by short-term simulation or machine learning methods for a more accurate prediction of conflicts and taxiing times.

The proposed joint IARA-IDRO operation impacts a number of other airport surface operations and initiatives such as those mentioned in Section 3.1. These systems and technologies can be further integrated with the proposed methods to achieve additional benefits for surface operation.

REFERENCES

ACI, 2007. Apron Marking & Signs Handbook. Second Edition ed. ACI world Headquaters, Switzerland: Airports Council International (ACI) world.

ACI, 2014. SESAR and the digital transformation of Europe's airports.

Adamson, P., 2006. Operational Concept and Requirements for A-SMGCS implementation Level 1.

Alecsandru, C. D.,2006. A stochastic mesoscopic cell-transmission model for operational analysis of large-scale transportation networks. *Louisiana State University and Agricultural & Mechanical College*. Doctoral dissertation.

Alers, T., 2013. Combining qualitative and quantitative measures for airport process analysis. *Aeronautic Study on Seamless Transport, 2013*, 1-7.

ARC, 2009. Study on the Impact of Directive 96/67/EC on Ground Handling Services 1996-2007. Aachen, Germany: Airport Research Centre.

Atkin, J., Burke, E., Ravizza, S., 2010. The airport ground movement problem: Past and current research and future directions. *In Proceedings of the 4th international conference on research in air transportation (ICRAT),* Budapest, Hungary, pp. 131-138.

Atkin, J., De Maere, G., Burke, E., Greenwood, J., 2013. Addressing the pushback time allocation problem at Heathrow airport. *Transportation Science, 47*(4), 584-602.

Atkins, S., Jung, Y., Brinton, C., Stell, L., Carniol, T., Rogowski, S., 2004. Surface management system field trial results. *In AIAA 4th Aviation Technology, Integration and Operations (ATIO) Forum,* p. 6241.

Babić, O., Teodorović, D., Tošić, V.,1984. Aircraft stand assignment to minimize walking. *Journal of Transportation Engineering, 110*(1), 55-66.

Balakrishnan, H., Jung, Y., 2007. A framework for coordinated surface operations planning at Dallas-Fort Worth International Airport. *In AIAA Guidance, Navigation and Control Conference and Exhibit,* p. 6553.

Balakrishna, P., Ganesan, R., Sherry, L., 2010. Accuracy of reinforcement learning algorithms for predicting aircraft taxi-out times: A case-study of Tampa Bay departures. *Transportation Research Part C: Emerging Technologies, 18*(6), 950-962.

Bandara, S., Wirasinghe, S. C., 1992. Walking distance minimization for airport terminal configurations. *Transportation Research Part A: Policy and Practice, 26*(1), 59-74.

Barrer, J., Kuzminski, P., Swedish, W., 2005. Analyzing the runway capacity of complex airports. *In AIAA 5th ATIO and16th Lighter-Than-Air Sys Tech. and Balloon Systems Conferences*, p. 7354.

BCIA, 2017. http://www.bcia.com.cn

Benlic, U., Brownlee, A. E., Burke, E. K., 2016. Heuristic search for the coupled runway sequencing and taxiway routing problem. *Transportation Research Part C: Emerging Technologies, 71,* 333-355.

Bennell, J. A., Mesgarpour, M., Potts, C. N., 2011. Airport runway scheduling. *4OR, 9*(2), 115-138.

Bertsimas, D., Frankovich, M., 2013. Air traffic flow management at airports: a unified optimization approach. *Tenth USA/Europe Air Traffic Management Research and Development.*

Bertsimas, D., Frankovich, M., 2016. Unified optimization of traffic flows through airports. *Transportation Science*, *50*(1), 77-93.

Biella, M., Hahn, K., Zilz, J., Lafferton, H., Vieten, B.D., Danello, F., 2015. Follow-the-greens: towards increased safety and efficiency by the use of airfield ground lighting (AGL). Results from a SESAR real time simulation.

Bihr, R. A., 1990. A conceptual solution to the aircraft gate assignment problem using 0, 1 linear programming. *Computers & Industrial Engineering*, *19*(1-4), 280-284.

Blumstein, A., 1959. The landing capacity of a runway. *Operations Research*, *7*(6), 752-763.

Blumstein, A., 1960. An analytical investigation of airport capacity. *CORNELL AERONAUTICAL LAB INC BUFFALO NY.*

Bowen, E. G., Pearcey, T., 1948. Delays in the flow of air traffic. *The Aeronautical Journal*, *52*(448), 251-258.

Bolender, M., Slater, G., 2000a. Analysis and optimization of departure sequences. In *AIAA Guidance, Navigation, and Control Conference and Exhibit*, p. 4475.

Bolender, M., 2000b. Scheduling and control strategies for the departure problem in air traffic control. *University of Cincinnati, United States, Ohio*. Doctoral dissertation.

Bosson, C. S., 2015. Optimisation integrated airport surface and terminal airspace operations under uncertainty. *Purdue University*. Doctoral dissertation.

BPR, 1964. Bureau of Public Roads. Traffic assignment manual for application with a large, high-speed computer (Vol. 37). *US Department of Commerce, Bureau of Public Roads, Office of Planning, Urban Planning Division.*

Braaksma, J. P., 1977. Reducing walking distances at existing airports. In *Airport Forum*. Vol. 7.

Brinton, C., Provan, C., Lent, S., Prevost, T., Passmore, S., 2011. Collaborative departure queue management. In *Ninth USA/Europe Air Traffic Management Research and Development Seminar (ATM2011)*.

CAAC, 2017. Civil Aviation Administration of China: National Civil Aviation Flight Operation Efficiency Report.

Castaing, J., Mukherjee, I., Cohn, A., Hurwitz, L., Nguyen, A., Müller, J. J., 2016. Reducing airport gate blockage in passenger aviation: Models and analysis. *Computers & Operations Research*, *65*, 189-199.

Cetek, C., Cinar, E., Aybek, F., Cavcar, A., 2014. Capacity and delay analysis for airport manoeuvring areas using simulation. *Aircraft Engineering and Aerospace Technology: An International Journal*, *86*(1), 43-55.

Chen, J., Stewart, P., 2011. Planning aircraft taxiing trajectories via a multi-objective immune optimisation. In *2011 Seventh International Conference on Natural Computation*. Vol. 4, pp. 2235-2240.

Chen, J., Weiszer, M., Stewart, P., 2015a. Optimal speed profile generation for airport ground movement with consideration of emissions. In *2015 IEEE 18th International Conference on Intelligent Transportation Systems*, pp. 1797-1802.

Chen, J., Weiszer, M., Stewart, P., Shabani, M., 2015b. Toward a more realistic, cost-effective, and greener ground movement through active routing—part i: Optimal speed profile generation. *IEEE Transactions on Intelligent Transportation Systems*, *17*(5), 1196-1209.

Chen, J., Weiszer, M., Locatelli, G., Ravizza, S., Atkin, J. A., Stewart, P., Burke, E. K., 2016. Toward a more realistic, cost-effective, and greener ground movement through active routing: a multiobjective shortest path approach. *IEEE Transactions on Intelligent Transportation Systems*, *17*(12), 3524-3540.

Chen, K., 2007. Research on airport capacity assessment. *Southwest Jiaotong University.* Master dissertation.

Cheng, C. H., Ho, S. C., Kwan, C. L., 2012. The use of meta-heuristics for airport gate assignment. *Expert systems with applications*, *39*(16), 12430-12437.

Clare, G., Richards, A., Sharma, S., 2009. Receding horizon, iterative optimization of taxiway routing and runway scheduling. In *AIAA Guidance, Navigation, and Control Conference*, p. 5646.

Clare, G., Richards, A. G., 2011. Optimization of taxiway routing and runway scheduling. *IEEE Transactions on Intelligent Transportation Systems*, *12*(4), 1000-1013.

Cohen, L., Morrison, L., 2002. Research methods in education. *Routledge.*

Commission Implementing Regulation, 2014. Pilot Common Project supporting the implementation of the European Air Traffic Management Master Plan. *EU No 716/2014.*

Commission Regulation, 2011. Detailed rules for the implementation of ATM network functions and amending Regulation (EU) N° 677/2011.

Communication Navigation Surveillance, 2014. Airports Authority of India.

Courant, R., Friedrichs, K., Lewy, H., 1928. Über die partiellen Differenzengleichungen der mathematischen Physik. *Mathematische annalen*, *100*(1), 32-74.

Daganzo, C. F., 1994. The cell transmission model: A dynamic representation of highway traffic consistent with the hydrodynamic theory. *Transportation Research Part B: Methodological*, *28*(4), 269-287.

Daganzo, C. F., 1995. The cell transmission model, part II: network traffic. *Transportation Research Part B: Methodological*, *29*(2), 79-93.

De Neufville, R., Odoni, A. R., Belobaba, P. P., Reynolds, T. G., 2013. *Airport systems: Planning, design, and management*. McGraw-Hill Education.

Deau, R., Gotteland, J. B., Durand, N., 2008. Runways sequences and ground traffic optimisation. In *ICRAT 2008, 3rd International Conference on Research in Air Transportation*.

Deau, R., Gotteland, J. B., Durand, N., 2009. Airport surface management and runways scheduling. In *ATM 2009, 8th USA/Europe Air Traffic Management Research and Development Seminar*.

Deonandan, I., Balakrishnan, H., 2010. Evaluation of strategies for reducing taxi-out emissions at airports. In *10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*.

Ding, H., Lim, A., Rodrigues, B., Zhu, Y., 2005. The over-constrained airport gate assignment problem. *Computers & Operations Research, 32*(7), 1867-1880.

Dorndorf, U., Jaehn, F., Pesch, E., 2008. Modelling robust flight-gate scheduling as a clique partitioning problem. *Transportation Science*, *42*(3), 292-301.

Dorndorf, U., Jaehn, F., Pesch, E., 2012. Flight gate scheduling with respect to a reference schedule. *Annals of Operations Research*, *194*(1), 177-187.

Dorndorf, U., Jaehn, F., Pesch, E., 2017. Flight gate assignment and recovery strategies with stochastic arrival and departure times. *Or Spectrum*, *39*(1), 65-93.

Dubouchet, E., Mavoian, G., Page, E., 1999. PHARE Advanced Tools Departure Manager Final Report. *PHARE Document DOC*, 98-70.

EUROCONTROL, 2001. Guidelines on Runway Capacity enhancement.

EUROCONTROL, 2003. Airside Capacity Enhancement (ACE) Implementation Manual - Edition 1.0.

EUROCONTROL, 2005. London Heathrow CDM WP1. Project London Heathrow CDM.

EUROCONTROL, 2006a. Safety Assessment of Airport Airside Capacity Enhancement.

EUROCONTROL, 2006b. Airport CDM operational concept document.

EUROCONTROL, 2006c. Total Airport Management: a step beyond Airport Collaborative Decision Making. *Report, EUROCONTROL*.

EUROCONTROL, 2007. An overview of the European Network Capacity Planning Process.

EUROCONTROL, 2008. European Medium-Term ATM Network Capacity Plan Assessment 2009-2012.

EUROCONTROL, 2009. European Medium-Term ATM Network Capacity Plan Assessment 2010-2013.

EUROCONTROL, 2010a. Arrival Manager: Implementation guidelines and lessons learned. *0.1, Brussels: EUROCONTROL*.

EUROCONTROL, 2010b. Definition of A-SMGCS implementation levels.

EUROCONTROL, 2010c. The EUROCONTROL DMAN prototype- Description of DMAN in the A-CDM context.

EUROCONTROL, 2010e. Operational concept and requirement for ASMGCS implementation Level 2.

EUROCONTROL, 2013a. European Route Network Improvement Plan. Part 1: European Airspace Design Methodology - Guidelines. *European Network Operations Plan.* Edition June 2015.

EUROCONTROL, 2013b. Capacity assessment and planning guidance document.

EUROCONTROL, 2013c. Challenges of Growth 2013.

EUROCONTROL, 2014c. Performance review report. An assessment of air traffic management in Europe during the calendar year 2013 draft final report for consultation with stakeholders.

EUROCONTROL, 2015. Airport CDM. What is Airport Collaborative Decision Making (A-CDM).

EUROCONTROL, 2016a. Airport Capacity Assessment Methodology, ACAM Manual.

EUROCONTROL, 2016b. Consolidated description of all active implementation objectives-Engineering view.

EUROCONTROL, 2017a. Airport CDM implementation. *Version 5.0.*

EUROCONTROL, 2017b. Airport CDM: Step to boost efficiency.

EUROCONTROL, 2018. European aviation in 2040. Challenges of growth.

EUROCONTROL, 2019. European Aviation Environmental Report 2019.

European Commission, 2015. Progress made in cutting emissions. https://ec.europa.eu/ claim/policies/strategies.

European Commission, 2016. European Network Operations Plan 2015 – 2019.

European Commission, 2017. Follow-the-Greens: the future of guidance is green.

Fairclough, I., 1999. PHARE Advanced Tools Arrival Manager Final Report. *PHARE Document DOC*, 98-70.

Federal Aviation Administration, 1968. Airport Capacity Criteria Used in Long Range Planning. Washington, DC: FAA No. 150/5060-3A.

Federal Aviation Administration, 1982. Airport and airway improvement amendments of 1982.

Federal Aviation Administration, 1983. Airport capacity and delay. FAA No.150/5060-5.

Federal Aviation Administration, 1987. Airport and airway improvement amendments of 1987.

Federal Aviation Administration, 1989. Airport Capacity Enhancement Plan. Washington, DC: DOT-TSC-FAA-89-1.

Federal Aviation Administration, 2012a. US Airport Surface Collaborative Decision Making (CDM) Concept of Operations (ConOps) in the Near-Term: Application of Surface CDM at United States Airports. FAA, June.

Federal Aviation Administration, 2012b. Aeronautical Information Manual, Chapter 2, Section 3: Airport Marking Aids and Signs.

Federal Aviation Administration, 2016. NextGen implementation plan 2016.

Federal Aviation Administration, 2019. Pilot/Controller Glossary.

Fines, K., Sharpanskykh, A., Vert, M., 2020. Agent-based distributed planning and coordination for resilient airport surface movement operations. *Aerospace*, *7*(4), 48.

Friesz, T. L., Han, K., Neto, P. A., Meimand, A., Yao, T., 2013. Dynamic user equilibrium based on a hydrodynamic model. *Transportation Research Part B: Methodological*, *47*, 102-126.

Furini, F., Persiani, C. A., Toth, P., 2012. Aircraft sequencing problems via a rolling horizon algorithm. In *International Symposium on Combinatorial Optimization*, pp. 273-284. Springer, Berlin, Heidelberg.

Garavello, M., Han, K., Piccoli, B., 2016. Models for vehicular traffic on networks. *AIMS Series on Applied Mathematics, Springfield.*

García, J., Berlanga, A., Molina, J. M., Casar, J. R., 2005. Optimization of airport ground operations integrating genetic and dynamic flow management algorithms. *AI Communications*, *18*(2), 143-164.

Gilbo, E., 1993. Airport capacity: representation, estimation, optimization. *IEEE Transactions on control systems technology*, *1*(3), 144-154.

Gilbo, E., Howard, K., 2000. Collaborative optimization of airport arrival and departure traffic flow management strategies for CDM. In *3rd USA/Europe Air Traffic Management R&D Seminar* (pp. 13-16).

Gluchshenko, O., 2012. Optimization of runway capacity utilization in the case of general pareto curve. In *Proceedings of 28th International Congress of the Aeronautical Sciences, Brisbane, Australia*.

Goh, J., Sim, M., 2010. Distributionally robust optimization and its tractable approximations. *Operations Research 58*(4), 902-917.

Gong, C., 2009. Kinematic airport surface trajectory model development. *In 9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO) and Aircraft Noise and Emissions Reduction Symposium (ANERS)*, p. 7076.

Gotteland, J. B., Durand, N., Alliot, J. M., Page, E., 2001. Aircraft ground traffic optimization. In *ATM 2001, 4th USA/Europe Air Traffic Management Research and Development Seminar*.

Guépet, J., Briant, O., Gayon, J. P., Acuna-Agost, R., 2017. Integration of aircraft ground movements and runway operations. *Transportation research part E: logistics and transportation review*, *104*, 131-149.

Günther, Y., Inard, A., Werther, B., Bonnier, M., Spies, G., Marsden, A., Niederstraßer, H., 2006. Total Airport Management (operational concept and logical architecture). Doctoral dissertation.

Guo, R., Zhang, Y., Wang, Q., 2014. Comparison of emerging ground propulsion systems for electrified aircraft taxi operations. *Transportation Research Part C: Emerging Technologies*, *44*, 98-109.

Gupta, G., Malik, W., Jung, Y., 2011. Effect of uncertainty on deterministic runway scheduling. In *11th AIAA Aviation Technology, Integration, and Operations (ATIO)*

Conference, including the AIAA Balloon Systems Conference and 19th AIAA Lighter-Than, p. 6924.

Haghani, A., Chen, M. C., 1998. Optimizing gate assignments at airport terminals. *Transportation Research Part A: Policy and Practice*, *32*(6), 437-454.

Han, K., Friesz, T. L., Szeto, W. Y., Liu, H., 2015. Elastic demand dynamic network user equilibrium: formulation, existence, and computation. *Transportation Research Part B: Methodological*, *81*, 183-209.

Harris, R.M., 1972. Models for runway capacity analysis. *The Mitre Corporation Technical Report 4102*, Washington D.C, 1-94.

Herrero, J. G., Berlanga, A., Molina, J. M., Casar, J. R., 2005. Methods for operations planning in airport decision support systems. *Applied Intelligence*, *22*(3), 183-206.

Horonjeff, R., McKelvey, F., Sproule, W., Young, S., 1962. Planning and design of airports (Vol. 3). *New York: McGraw-Hill.*

Hu, M., Liu, S., 2000. Research on single runway capacity assessment model based on statistical analysis. *Data Acquisition and Processing,*

IATA, 2013. IATA Reference Manual for Audit Programs (IRM). *4th edition ed. Montreal, Canada: International Air Transport Association*.

IATA, 2015. IATA Ground Operations Manual (IGOM). Montreal, Canada: International Air Transport Association (IATA).

IATA, 2021. IATA Reference Manual for Audit Programs. *11th edition.*

ICAO, 2005a. *Doc 9854: Global Air Traffic Management Operational Concept*, First edition.

ICAO, 2005b. Doc 9157: Aerodrome Design Manual Part 2: Taxiways, aprons and holding bays. *Fourth edition.*

ICAO, 2007. Doc. 8400: Abbreviations and codes.

ICAO, 2009. Doc. 9883: Manual on Global Performance of the Air Navigation System. *First edition.*

ICAO, 2010. Annex 16 to the Convention on International Civil Aviation. Operation of Aircraft. Part I: International Commercial Air Transport- Aeroplanes. *Nineth Edition*.

ICAO, 2013. Doc. 9161: Manual on Air Navigation Service Economics. Fifth edition.

ICAO, 2016a. Annex 14 to the Convention on International Civil Aviation: Aerodromes (Volume 1: Aerodrome design and operation).

ICAO, 2016b. Doc. 4444: Air Traffic Management. *Sixteenth Edition.*

ICAO, 2018. Runway and Ground Safety Working Group. *Fifth Meeting (RGS WG/5), Cairro, Egypt, 25-28 November 2018.*

Idris, H., Clarke, J. P., Bhuva, R., Kang, L., 2001. *Queuing model for taxi-out time estimation*. *Air Traffic Control Quarterly 10*(1), 1-22.

Jacquillat, A., Odoni, A. R., 2015. An integrated scheduling and operations approach to airport congestion mitigation. *Operations Research*, *63*(6), 1390-1410.

Jacquillat, A., Odoni, A. R., Webster, M. D., 2017. Dynamic control of runway configurations and of arrival and departure service rates at JFK airport under stochastic queue conditions. *Transportation Science*, *51*(1), 155-176.

Jiang, B., Hu, M., Tian, Y., Huang, W., 2003. Further research of airport runway capacity evaluation. *Journal of Traffic and Transportation Engineering*, *2*(3), 80-883.

Jin, W., Zhang, H., 2003. On the distribution schemes for determining flows through a merge. *Transportation Research Part B: Methodological, 37,* 521–540.

Jung, Y., 2019. Spot and Runway Departure Advisor (SARDA) Technical Overview. In NASA-KAIA (Korea Agency for Infrastructure Technology Advancement)/KARI/IIAC Collaboration Kickoff Meeting (No. ARC-E-DAA-TN22938).

Kamat, V. R., Martinez, J. C., 2003. Validating complex construction simulation models using 3D visualization. *Systems Analysis Modelling Simulation, 43*(4), 455-467.

Keith, G., Richards, A., Sharma, S., 2008. Optimization of taxiway routing and runway scheduling. In *AIAA Guidance, Navigation and Control Conference and Exhibit*, p. 6827.

Khadilkar, H., Balakrishnan, H., 2012. Estimation of aircraft taxi fuel burn using flight data recorder archives. *Transportation Research Part D: Transport and Environment*, *17*(7), 532-537.

Kicinger, R., Krozel, J., Steiner, M., Pinto, J., 2012. Airport capacity prediction integrating ensemble weather forecasts. In *Infotech@ Aerospace 2012*, p. 2493.

Kim, S. H., Feron, E., Clarke, J. P., 2010. Airport gate assignment that minimizes passenger flow in terminals and aircraft congestion on ramps. In *AIAA Guidance, Navigation, and Control Conference*, p. 7693.

Kim, S. H., Feron, E., Clarke, J. P., 2013. Gate assignment to minimize passenger transit time and aircraft taxi time. *Journal of Guidance, Control, and Dynamics*, *36*(2), 467-475.

Kjenstad, D., Mannino, C., Nordlander, T. E., Schittekat, P., Smedsrud, M., 2013. Optimizing AMAN-SMAN-DMAN at Hamburg and Arlanda airport. *Proceedings of the SID, Stockholm*.

Kratudnak, S., Tippayawong, K. Y., 2018. Analysis of key factors for airport service quality: A case study of three regional airports in Thailand. *In International Conference on Industrial Engineering and Operations Management.* Bandung, Indonesia.

Krozel, J., Prete, J., Mitchell, J., Kim, J., Zou, J., 2008. Capacity estimation for super-dense operations. In *AIAA Guidance, Navigation and Control Conference and Exhibit*, p. 7226.

Kumar, V., Sherry, L., Thompson, T., 2008. Analysis of emissions inventory for 'single-engine taxi-out' operations. In *International Conference on Research in Air Transportation,* pp. 1-6.

Lee, J., Chen, D., Balakrishnan, V., Koh, C. K., Jiao, D., 2012. A quadratic eigenvalue solver of linear complexity for 3-D electromagnetics-based analysis of large-scale integrated

circuits. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems, 31*(3), 380-390.

Lee, D. A., Nelson, C., Shapiro, G., 1998. The aviation system analysis capability airport capacity and delay models. *National Aeronautics and Space Administration, Langley Research Centre.*

Lighthill, M. J., Whitham, G. B., 1955. On kinematic waves II. A theory of traffic flow on long crowded roads. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, *229*(1178), 317-345.

Lim, A., Rodrigues, B., Zhu, Y., 2005. Airport gate scheduling with time windows. *Artificial Intelligence Review*, *24*(1), 5-31.

Lim, A., Wang, F., 2005. Robust airport gate assignment. In *17th IEEE International Conference on Tools with Artificial Intelligence*.

Lordan, O., Sallan, J. M., Valenzuela-Arroyo, M., 2016. Forecasting of taxi times: The case of Barcelona-El Prat airport. *Journal of Air Transport Management*, *56*, 118-122.

Ma, J., Delahaye, D., Sbihi, M., Mongeau, M., 2016. Integrated optimization of terminal manoeuvring area and airport. *6th SESAR Innovation Days*.

Ma, J., Delahaye, D., Sbihi, M., Scala, P., 2018. Integrated Optimization of arrival, departure, and surface operations. In *ICRAT 2018, 8th International Conference for Research in Air Transportation*. Federal Aviation Administration and EUROCONTROL.

Ma, Y., Hu, M., Yin, J., Tian, W., 2015. Collaborative sequencing method of arrivals in multi-airport terminal. *Acta Aeronautics Sinica 36*(7), 2279-2290.

Maerivoet, S., De Moor, B., 2005. Cellular automata models of road traffic. *Physics reports, 419*(1), 1-64.

Maharjan, B., Matis, T. I., 2011. An optimization model for gate reassignment in response to flight delays. *Journal of Air Transport Management*, *17*(4), 256-261.

Mangoubi, R. S., Mathaisel, D. F., 1985. Optimizing gate assignments at airport terminals. *Transportation Science*, *19*(2), 173-188.

Marín, Á., 2006. Airport management: taxi planning. *Annals of Operations Research*, *143*(1), 191-202.

Marín, Á., Codina, E., 2008. Network design: taxi planning. *Annals of Operations Research*, *157*(1), 135-151.

Marín, Á., 2013. Airport taxi planning: Lagrangian decomposition. *Journal of Advanced Transportation, 47*(4), 461-474.

Mascia, M, Hu, J, Han, K, North, R, Van Poppel, M, Theunis, J, Litzenberger, M, 2016. Impact of traffic management on black carbon emissions: A microsimulation study. *Networks and Spatial Economics, 17*(1), 269-291.

Mazur, F., Schreckenberg, M., 2018. Simulation and optimization of ground traffic on airports using cellular automata. *Collect. Dyn, 3*, 1-22.

Merkisz-Guranowska, A., Bienczak, M., Kicinski, M., Zmuda-Trzebiatowski., P., 2016. Location of airports-selected quantitative methods. *LogForum, 12*(3).

Milan, J., 1997. The flow management problem in air traffic control: a model of assigning priorities for landings at a congested airport. *Transportation Planning and Technology*, *20*(2), 131-162.

Musa, M., Lsha, A.S.N., 2021. Holistic view of safety culture in aircraft ground handling: Integrating quatlitative and quantitative methods with data triangulation. *Journal of Air Transport Management, 92*, 102019.

Nagel, K., Schreckenberg, M., 1992. A cellular automaton model for freeway traffic. Journal de physique I, 2(12), 2221-2229. Newell, G. F., 1979. Some issues relating to the optimal design of bus routes. *Transportation Science*, *13*(1), 20-35.

Nikoleris, T., Gupta, G., Kistler, M., 2011. Detailed estimation of fuel consumption and emissions during aircraft taxi operations at Dallas/Fort Worth International Airport. *Transportation Research Part D: Transport and Environment*, *16*(4), 302-308.

O'Brien, M., 2008. IATA's Safety Audit for Ground Operations (ISAGO). *International Airport Review*, *12*(5).

Online News, 2021. London City Airport's air traffic becomes full remotely controlled. https://www.airport-technology.com/news/london-city-airports.

Oppenheim, A. N., 2000. Questionnaire design, interviewing and attitude measurement. *Bloomsbury Publishing.*

Pavese, G., Bruglieri, M., Rolando, A., Careri, R., 2017. DMAN-SMAN-AMAN optimisation at milano linate airport. *Eigth SESAR Innovation Days*.

Pesic, B., Durand, N., Alliot, J. M., 2001. Aircraft ground traffic optimisation using a genetic algorithm. HAL Id: hal-00938003.

Phillips, C., McCarthy, M., Barrowcliffe, R., 2010. Methods for quantitative health impact assessment of an airport and waste incinerator: two case studies. *Impact Assessment and Project Appraisal*, 1461-5517.

PRC, 2015. Performance Review Commission, FAA-ATO. U.S./Europe Comparison of ATM-related Operational Performance.

PRC, 2018. Performance Review Commission, FAA-ATO.U.S./Europe Comparison of ATM-related Operational Performance.

Pujet, N., Feron, E., Rakhit, A., 1998. Modeling of an airline operations control center as a queueing network. In *Proceedings of the 1998 American Control Conference. ACC (IEEE Cat. No. 98CH36207)*. Vol. 3, pp. 1800-1803.

Puranik, T.G., 2018. A methodology for quantitative data-driven safety assessment for general aviation. *Georgia Institute of Technology.* Doctoral dissertation.

Qiu, Z., 2012. Research on departure strategy of multi-airport in the pearl river delta region. *Nanjing University of Aeronautics and Astronautics*. Master dissertation.

Rathinam, S., Montoya, J., Jung, Y., 2008. An optimization model for reducing aircraft taxi times at the Dallas Fort Worth International Airport. In *26th International Congress of the Aeronautical Sciences (ICAS)*, pp. 14-19.

Ravizza, S., Atkin, J. A., Maathuis, M. H., Burke, E. K., 2013a. A combined statistical approach and ground movement model for improving taxi time estimations at airports. *Journal of the Operational Research Society*, *64*(9), 1347-1360.

Ravizza, S., Chen, J., Atkin, J. A., Burke, E. K., Stewart, P., 2013b. The trade-off between taxi time and fuel consumption in airport ground movement. *Public Transport*, *5*(1-2), 25-40.

Robinson, III, J., Davis, T., Isaacson, D., Robinson, III, J., Davis, T., Isaacson, D., 1997. A fuzzy reasoning-based sequencing of arrival aircraft in the terminal area. In *Guidance, Navigation, and Control Conference*, p. 3542.

Roling, P. C., Visser, H. G., 2008. Optimal airport surface traffic planning using mixed-integer linear programming. *International Journal of Aerospace Engineering*. Doi: 10.1155/2008/732828.

Sanchez, R., D., 2019. Airport ground movement simulation using cellular automata: Beijing Case Study. *Imperial College London*. Master dissertation.

Saraf, A. P., Slater, G. L., 2006. An efficient combinatorial optimization algorithm for optimal scheduling of aircraft arrivals at congested airports. In *2006 IEEE Aerospace Conference*, pp. 11-pp.

Savin-Baden, M., Howell-Major, C., 2013. Qualitative research: The essential guide to theory and practice. *Routledge.*

Shorten, A., Smith, J., 2017. Mixed methods research: expanding the evidence base. *Evidence-based nursing, 20*(3), 74-75.

Shortle, J., 2006. Quantitative methods for safety analysis in aviation. Online available:

https://catsr.vse.gmu.edu/IntroATC/SafetyTutorial_ICRAT.pdf

Shyur, H.J., 2008. A quantitative model for aviation safety risk assessment. *Computers & Industrial engineering, 54*(1), 34-44.

Sidiropoulos, S., Majumdar, A., Ochieng, W. and Schuster, W., 2015a. Levels of organization in multi-airport systems. *Transportation Research Board 94th Annual Meeting Washington*, DC, USA.

Sidiropoulos, S., Majumdar, A., Han, K., Schuster, W., Ochieng, W., 2015. A framework for the classification and prioritization of arrival and departure routes in Multi-Airport Systems Terminal Manoeuvring Areas. *In 15th AIAA Aviation Technology, Integration, and Operations Conference,* p. 3031.

Sidiropoulos, S., 2016. A framework for the optimisation of terminal airspace design in Multi-Airport Systems. *Imperial College London*. Doctoral dissertation.

Sidiropoulos, S., Majumdar, A., Han, K., 2018. A framework for the optimization of terminal airspace operations in Multi-Airport Systems. *Transportation Research Part B: Methodological, 110*, 160-187.

Simpson, R. W., Odoni, A. R., Salas-Roche, F., 1986. Potential impacts of advanced technologies on the ATC capacity of high-density terminal areas. *Cambridge, Mass.: MIT, Dept. of Aeronautics & Astronautics, Flight Transportation Laboratory.*

Simaiakis, I., Balakrishnan, H., 2016. A queuing model of the airport departure process. *Transportation Science, 50*(1), 94-109.

Simaiakis, I., Khadilkar, H., Balakrishnan, H., Reynolds, T. G., Hansman, R. J., 2014. Demonstration of reduced airport congestion through pushback rate control. *Transportation Research Part A: Policy and Practice*, *66*, 251-267.

SJU, 2012a. European ATM master plan: the roadmap for sustainable air traffic management. Brussel, Belgium: SESAR Joint Undertaking.

SJU, 2012b. SESAR Concept of operation Step 1. D65-011. 01.00.00 ed. Brussel, Belgium: SESAR Joint Undertaking.

SJU, 2013. SESAR concept of operation step 2. Brussel, Belgium: SESAR Joint Undertaking.

SJU, 2014a. GGSWIM-60b provision of ground- ground data SWIM enabled services for network operations planning available in step 2. Brussel, Belgium: SESAR Joint Undertaking.

SJU, 2014b. GGSWIM-69b provision of ground- ground data SWIM enabled services for airport ono exchange available in step 2. Brussel, Belgium: SESAR Joint Undertaking.

SJU, 2014c. GGSWIM-71b. Use of ground-ground SWIM enable services for AOC information exchange available in step 2. Brussel, Belgium: SESAR Joint Undertaking.

SJU, 2014d. IS-0902 SWIM for step 2. Brussel, Belgium: SESAR Joint Undertaking.

SJU, 2015a. SESAR Deployment Manager: A-SMGCS Planning and routing workshop.

SJU, 2015b. European ATM Master Plan.

SJU，2017a. Virtual stop bars: from block control towards low visibility automation support.

SJU, 2017b. Europe's next step in Airport Performance Management Research. SESAR 2020 Project PJ.04, Total Airport Management.

SJU, 2018a. Arrival Management (AMAN) and point merge.

SJU, 2018b. Extended AMAN. SESAR Deployment Manager Workshop. Brussels.

SJU, 2018c. DMAN Baseline for integrated AMAN/DMAN.

SJU, 2018d. Pre-Departure sequencing supported by taxiing route.

SJU, 2020. Master Plan Edition, 2020. S-AF 2.1.

Smeltink, J. W., Soomer, M. J., 2004. An optimisation model for airport taxi scheduling. *In INFORMS Annual Meeting,* Denver, CO, USA.

Smith, C., Piggott, A., Morris, C., 1998. Final approach spacing tool. *Proceedings of 2nd USA/Europe ATM Research and Development Seminar*. Orlando.

Stettler, M. E. J., Koudis, G. S., Hu, S. J., Majumdar, A., Ochieng, W. Y., 2018. The impact of single engine taxiing on aircraft fuel consumption and pollutant emissions. *The Aeronautical Journal*, *122*(1258), 1967-1984.

Studic, M., 2013. Preparing planes for take-off: looking at what happens on the apron during turnarounds. *7th FRAM- Workshop on the Functional Resonance Analysis Method (FRAM) for Modelling Complex Socio- Technical Systems.*

Studic, M., 2014. A framework to assess the impact of airport interaction into the Air Traffic Management (ATM) system safety. *8th FRAM- Workshop on the Functional Resonance Analysis Method (FRAM) for Modelling Complex Socio- Technical Systems.*

Studic, M., Schuster, W., Crespo, A. M. F., Majumdar, A., Ochieng, W., 2015. The case for SMS requirements for ground service providers. In *The 19th Air Transport Research Sosciety (ATRS) World Conference. Singapore*.

Studic, M., 2016. Developing a framework for Total Apron Safety Management. *Imperial College London.* Doctoral dissertation.

Szeto, W. Y., Wang, Y., Han, K., 2015. Bounded rationality in dynamic traffic assignment. In *Bounded rational choice behaviour: Applications in transport*, 978-1-78441-072-8.

TAMS Partners, 2012. TAMS Operational Concept Document TAMS OCD. *1-0-1 ed. Germany: DLR.*

Wang, Q., 2014. Real-time integrated airport surface operations management (RTI-ASOM). In *2014 Integrated Communications, Navigation and Surveillance Conference (ICNS) Conference Proceedings,* pp. 1-35.

Wang, X., Brownlee, A. E., Woodward, J. R., Weiszer, M., Mahfouf, M., Chen, J., 2021. Aircraft taxi time prediction: Feature importance and their implications. *Transportation Research Part C: Emerging Technologies*, *124*, 102892.

Weiszer, M., Chen, J., Ravizza, S., Atkin, J., Stewart, P., 2014. A heuristic approach to greener airport ground movement. In *2014 IEEE congress on evolutionary computation (CEC)*, pp. 3280-3286.

Weiszer, M., Chen, J., Stewart, P., 2015a. A real-time active routing approach via a database for airport surface movement. *Transportation Research Part C: Emerging Technologies*, *58*, 127-145.

Weiszer, M., Chen, J., Locatelli, G., 2015b. An integrated optimisation approach to airport ground operations to foster sustainability in the aviation sector. *Applied Energy*, *157*, 567-582.

Weiszer, M., Chen, J., Stewart, P., Zhang, X., 2018. Preference-based evolutionary algorithm for airport surface operations. *Transportation Research Part C: Emerging Technologies*, *91*, 296-316.

Wilke, S., Majumdar, A., Ochieng, W. Y., 2012. Holistic approach to airport surface safety. *Transportation research record*, *2300*(1), 1-12.

Wilke, S., 2013. Modelling airport surface safety: a framework for a holistic airport safety management. *Imperial College London*. Doctoral dissertation.

Wilke, S., Majumdar, A., Ochieng, W. Y., 2014. A framework for assessing the quality of aviation safety databases. *Safety Science*, *63*, 133-145.

Yan, S., Tang, C. H., 2007. A heuristic approach for airport gate assignments for stochastic flight delays. *European Journal of Operational Research*, *180* (2), 547-567.

Yang, L., Yin, S., Han, K., Haddad, J., Hu, M., 2017. Fundamental diagrams of airport surface traffic: Models and applications. *Transportation research part B: Methodological*, *106*, 29-51.

Yin, M., 2018. Research on efficiency promotion techniques of airport surface operation. *Nanjing University of Aeronautics and Astronautics*. Master dissertation.

Yin, J., 2016. Management and control method for airfield area operations at complex airport. *Nanjing University of Aeronautics and Astronautics*. Doctoral dissertation.

Yin, S., 2015. Research on departure operation analysis and gate collaborative control at Mega-airport. *Nanjing University of Aeronautics and Astronautics*. Master dissertation.

Yin, S., Han, K., Ochieng, W.Y., Sanchez, D., 2022. Joint apron-runway assignment for airport surface operations. *Transportation research part B: Methodological*, *156*, 76-100.

Ying, S., Sun, F., et al., 2011. Multi-runways arrival sequence based on multi-objective dynamic programming. *Control Theory and Application.27*(7), 827-835.

Yu, C., Lau, H., 2014. Integrated optimization of airport taxiway and runway scheduling. *Journal of Automation and Control Engineering*, *2*.

Yu, C., Zhang, D., Lau, H. Y., 2016. MIP-based heuristics for solving robust gate assignment problems. *Computers & Industrial Engineering*, *93*, 171-191.

Zhang, D., Klabjan, D., 2017. Optimization for gate re-assignment. *Transportation Research Part B: Methodological*, *95*, 260-284.

Zhang, T., Ding, M., Zuo, H., Chen, J., Weiszer, M., Qian, X., Burke, E. K., 2018. An online speed profile generation approach for efficient airport ground movement. *Transportation Research Part C: Emerging Technologies*, *93*, 256-272.

Zhang, Z., Wang, L., 2004. Dynamic sorting algorithm for air traffic management based on flow and rolling window. *Journal of Transportation Engineering and Letters, 2*(3),22-25

Zhu, D., 1998. Determination of airport runway capacity under radar control conditions. *Civil Aviation Economics and Technology. Vol. 12,* 26-28.

APPENDICES

Appendix 1. Definition of Key Performance Areas by ICAO

A total of eleven Key Performance Areas (KPAs) are defined in the Manual on Global Performance of the Air Navigation System (ICAO, 2009, p. App E-1 to E-7), which are used to measure ATM performances and indicate the direction of development direction of the civil aviation up to 2025 and beyond. The definition of each KPA is introduced as follows:

- **Access and equity.** *ATM should provide an operating environment that ensures that all airspace users have right of access to the ATM resources needed to meet their specific operational requirements and that the shared use of airspace by different users can be achieved safely. The global ATM system should ensure equity for all users that have access to a given airspace or service. Generally, the first aircraft ready to use the ATM resources will receive priority, except where significant overall safety or system operational efficiency would accrue, or national defence considerations or interests dictate by providing priority on a different basis.*
- **Capacity.** *The global air navigation system should exploit the inherent capacity to meet airspace user demand at peak times and locations while minimising restrictions on traffic flow. To respond to future growth, capacity must increase, along with corresponding increases in efficiency flexibility, and predictability while ensuring that there are no adverse impacts to safety giving due consideration to the environment. The air navigation system must be resilient to service disruption and the resulting temporary loss of capacity.*

- **Cost-effectiveness.** *The air navigation system should be cost effective, while balancing the varied interests of the ATM community. The cost of service to airspace users should always be considered when evaluating any proposal to improve ATM service quality or performance. ICAO guidelines regarding user charge policies and principles should be followed.*

- **Efficiency.** *Efficiency addresses the operational and economic cost effectiveness of gate-to-gate flight operations from a single-flight perspective. Airspace users want to depart and arrive at the times they select and fly the trajectory they determine to be optimum in all phases of flight.*

- **Environment.** *The air navigation system should contribute to the protection of the environment by considering noises, gaseous emissions, and other environmental issues in the implementation and operation of the global air navigation system.*

- **Flexibility.** *Flexibility addresses the ability of all airspace users to modify flight trajectories dynamically and adjust departure and arrival times thereby permitting them to exploit operational opportunities as they occur.*

- **Global interoperability.** *The air navigation system should be based on global standards and uniform principles to ensure the technical and operational interoperability of air navigation systems and facilitate homogeneous and non-discriminatory global and regional traffic flows.*

- **Participation by the ATM community.** *The ATM community should continuously be involved in the planning, implementation, and operation of the system to ensure that the evolution of the global air navigation system meets the expectations of the community,*

- **Predictability.** *Predictability refers to the ability of the airspace users and air navigation service providers to provide consistent dependable levels of performance. Predictability is essential to airspace users as they develop and operate their schedules.*

- **Safety.** *Safety is the highest priority in aviation, and ATM plays an important part in ensuring overall aviation safety. Uniform safety standards and risk and safety management practices should be applied systematically to the ATM system. In implementing elements of the global*

aviation system, safety needs to be assessed against appropriate criteria and in accordance with appropriate and globally standardized safety management processes and practices.

- **Security.** *Security refers to the protection against threats that stem from intentional acts (e.g. terrorism) or unintentional acts (e.g. human error, natural disaster) affecting aircraft, people or installations on the ground. Adequate security is a major expectation of the ATM community and of citizens. The ATM system should therefore contribute to security, and the ATM system, as well as ATM-related information, should be protected against security threats. Security risk management should balance the needs of the members of the ATM community that require access to the system, with the need to protect the ATM system. In the event of threats to aircraft or threats using aircraft, ATM shall provide the authorities responsible with appropriate assistance and information.*

Appendix 2. Examples of real-world data at PEK[21]

F.N.	F.R.	A.R	A.C.	A/D	D/I	STA	ELDT	ATA	STD	CTOT	ATOT	Stand	Terminal	AIBT	TOBT	AOBT	RWY
MH360	KUL	9MMTF	H	A	I	00:20	01:16	01:05				511	3	01:33			36L
MH361	KUL	9MMTF	H	D	I				01:30	02:20	02:59	511	3		01:55	02:30	36R
SQ806	SIN	9VSWH	SH	A	I	23:00	23:22	23:14				513	3	23:36			36L
CA1455	MIG	B1956	M	D	D				18:10	19:30	19:37	320	3	19:13			36R
3U8883	CTU	B2371	M	A	D	12:15	12:37	12:37				329	3	12:47			01
3U8884	CTU	B2371	M	D	D				13:30	13:58	14:04	329	3		13:39	13:45	36R
CA1877	ZHA	B7596	M	D	D				12:45	12:45	12:52	404	3		12:33	12:40	36R
HU7466	CGQ	B1489	M	A	D	17:00	16:40	16:40				108	1	16:46			36L
MU5713	KMG	B1307	M	A	D	12:00	13:25	13:18				229	2	13:26			36L
MU5714	KMG	B1307	M	D	D				13:10	14:00	14:39	229	2		13:40	14:20	36L
D7316	KUL	9MXXJ	H	A	I	01:05	01:22	01:10				214	2	01:24			36L
CZ318	GMP	B1802	M	A	I	13:35	13:17	13:13				205	2	13:32			01
SQ802	SIN	9VSKE	SH	A	I	14:40	14:37	14:36				508	3	14:42			01
HU7701	SZX	B1539	SH	D	D				17:15	17:50	18:38	W107	1		17:33	18:24	36L

[21] F.N (Flight Number); F.R. (Flight Route); A.R. (Aircraft Registration); A.C. (Aircraft Category); A/D (Arrival/Departure); D/I (Domain/International flights).

Appendix 3. Examples of aircraft basic information

Code	Aircraft Types	Length (m)	Number of occupied cells	Category
74Z	Boeing 747-8 Freighter	76	15	SH
748	Boeing 747-8I	76	15	SH
380	Airbus 380-800	73	15	SH
346	Airbus 340-600	75	15	H
773	Boeing 777-300	74	15	H
74Y	Boeing 747-400 Freighter	71	14	H
744	Boeing 747-400	71	14	H
359	Airbus350-900	67	13	H
333	Airbus 330-300	64	13	H
772	Boeing 777-200	64	13	H
343	Airbus 340-300	64	13	H
77F	Boeing 777 Freighter	64	13	H
789	Boeing 787-900	63	13	H
332	Airbus 330-200	59	12	H
788	Boeing 787-800	57	11	H
763	Boeing 767-300	55	11	H
AB6	Airbus 300-600	54	11	H
752	Boeing 757-200	47	9	H
TU2	Tupolev 204/214	46	9	M
321	Airbus 321-200	45	9	M
739	Boeing 737-900	42	8	M
738	Boeing 737-800	40	8	M
320	Airbus 320-100/200	38	8	M
73G	Boeing 737-700	37	7	M
734	Boeing 737-400	36	7	M
319	Airbus 319-100/200	34	7	M
733	Boeing 737-300	33	7	M
73Y	Boeing 737-300 Freighter	33	7	M
ER3	Embraer RJ135	26	5	M

Appendix 4. IATA Codes for Airports and Airlines

AIRLINE IATA 2-LETTER CODE

Code	Company Name	Code	Company Name
2D	Eastern Airlines	LH	Deutsche Lufthansa
3U	Sichuan Airlines	LO	LOT Polish Airlines
5J	Cebu Air	LX	SWISS International Air Lines
7C	Jeju Air	LY	El Al Israel Airlines
7J	Tajik Air	PS	Ukraine International Airlines
8L	Lucky Air	T5	Turkmenistan Airlines
9C	Spring Airlines	TG	Thai Airways
AA	American Airlines	J2	Azerbaijan Airlines
AC	Air Canada	JD	Beijing Capital Airlines
AF	Air France	JS	Air Koryo
AH	Airhub Airlines Limited	KY	Kunming Airlines
AL	Malta Air Ltd.	LV	Openskies
AY	Finnair Oyj	MF	Xiamen Airlines
AZ	Italia Trasporto Aereo	MH	Malaysia Airlines
BA	British Airways	MK	Air Mauritius
BR	EVA Airways Corporation	MS	Egyptair Airlines
CA	Air China	MU	China Eastern Airlines
CI	China Airlines	N4	LLC "Nord Wind"
CN	Grand China Air	NH	Nippon Airways
CX	Cathay Pacific Airways	NN	Hong Kong Limited
CZ	China Southern Airlines	NS	Hebei Airlines
D7	Airasia X Berhad	NX	Air Macau
DL	Delta Air Lines	OM	MIAT Mongolian Airlines
DT	Linhas Aereas de Angola	OS	Austrian Airlines
DZ	Donghai Airlines	OQ	Chongqing Airlines
EK	Emirates	OZ	Asiana Airlines
ET	Ethiopian Airlines Group	PK	Pakistan International Airlines
EY	Etihad Airways	PR	Philippine Airlines
FU	Fuzhou Airlines	QR	Qatar Airways
FM	Shanghai Airlines	QW	Qingdao Airlines
GA	Garuda Indonesia	R3	Yakutia
GH	Galistair Trading	S7	JSC Siberia Airlines
GJ	Zhejiang Loong Airlines	SC	Shandong Airlines
GS	TianJin Airlines	SK	Scandinavian Airlines
HA	Hawaiian Airlines	SQ	Scandinavian Airlines
HM	Air Seychelles	SU	PJSC Aeroflot

HO	Juneyao Airlines	TK	Turkish Airlines
HU	Hainan Airlines	TV	Tibet Airlines
HX	Hong Kong Airlines	U6	Ural Airlines
HY	Uzbekistan Airways	UA	United Airlines
HZ	Aurora Airlines	UL	SriLankan Airlines
IR	Iran Air	UN	Transaero Airlines
JL	Japan Airlines	VN	Vietnam Airlines
KA	Aero Nomad Airlines	W5	Mahan Air
KC	JSC AIR ASTANA	Y7	NordStar Airlines
KE	Korean Air Lines	ZA	Sky Angkor Airlines
KLM	Royal Dutch Airlines	ZH	Shenzhen Airlines

AIRPORT IATA CODE

AMS	Amsterdam Airport Schiphol
ATL	Hartsfield–Jackson Atlanta International Airport
CAN	Guangzhou Baiyun international airport
DEN	Denver International Airport
DFW	Dallas-Fort Worth International Airport
DTW	Detroit Metropolitan Airport
FRA	Frankfurt Airport
HEL	Helsinki Airport
IAD	Washington Dulles International Airport
IAH	George Bush Intercontinental Airport
KOA	Kona International Airport
LHR	Heathrow International Airport
MEM	Memphis International Airport
NGB	Ningbo Lishuo International airport
ORD	O'Hare International Airport
ORY	Paris Orly Airport
PEK	Beijing Capital International Airport
PKX	Beijing Daxing International Airport
STN	London Stansted Airport
TAO	Qingdao Liuting International Airport
URC	Xinjiang Diwopu International Airport