A FRAMEWORK FOR THE ANALYSIS OF AIRCRAFT TURNAROUND AT CONGESTED AIRPORTS

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A FRAMEWORK FOR THE ANALYSIS OF AIRCRAFT TURNAROUND AT CONGESTED AIRPORTS

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TABLE OF CONTENTS

ACKNOWLEDGEMENTS **iii**

LIST OF TABLES **viii**

LIST OF FIGURES **xiii**

SUMMARY **xxi**

CHAPTER 1. Introduction **1**
1.1 Motivation **4**
  1.1.1 Increasing Delay 4
  1.1.2 Cause of Delay 5
  1.1.3 Delay Handling Cost 7
1.2 Research Objective **8**

CHAPTER 2. BACKGROUND **10**
2.1 Aircraft Turnaround Process at Airports **12**
  2.1.1 Definition of Aircraft Turnaround Process 12
  2.1.2 Definition of Aircraft Turnaround Process Time 13
  2.1.3 Categories of Aircraft Turnaround Process 15
2.2 Analysis of the Current Aircraft Turnaround Process **16**
  2.2.1 Enhancement of the Aircraft Turnaround Process 17
  2.2.2 Modeling of the Aircraft Turnaround Process 20
  2.2.3 Operational Scenarios of the Aircraft Turnaround Process 25

CHAPTER 3. Approach **29**
3.1 Proposed Approach **32**
  3.1.1 Research Scope 33
  3.1.2 Application of Integrated Work Structure 34
3.2 Modeling and Simulation **37**
  3.2.1 Life Cycle 40
  3.2.2 Cost Modeling 43
3.3 Performance Evaluation **46**
  3.3.1 Queuing Criteria 46
  3.3.2 Turnaround Time Allocation (TTA) Model 47

CHAPTER 4. Input modeling **50**
4.1 Flight Data Analysis **55**
  4.1.1 Annual Data Analysis 55
  4.1.2 Flight Arrival in 2017 57
  4.1.3 Summary 66
4.2 Operational Scenarios **67**
  4.2.1 Busy: July 68
  4.2.2 Normal: November 74

4.2.3 Summary 79

4.3 Turnaround Process and Time 81

4.3.1 Boeing 82

4.3.2 Airbus 101

4.3.3 Standard Format of Turnaround Process 123

4.3.4 Resources 135

CHAPTER 5. Simulation Modeling 137

5.1 The Sequence of Ground Handling Activities 138

5.2 Critical Path 141

5.3 Model Development 142

5.3.1 Conceptual Modeling 142

5.3.2 Simulator Development 146

5.3.3 Data Format 155

5.4 Design of Experiment 156

5.4.1 Environment 157

5.4.2 List of Parameters 158

5.5 Summary 166

CHAPTER 6. Performance Evaluation 167

6.1 Key Components of Experiments 167

6.2 Boundary Condition 169

6.2.1 Number of Resources 169

6.2.2 Schedule Variability Buffer 178

6.3 Experiments Evaluation under Nominal Condition 183

6.3.1 First-Come-First-Served (FCFS) 184

6.3.2 Schedule Departure Time (SDT) 201

6.3.3 Comparison of Operational Strategy under the Nominal Scenarios 213

6.4 Experiments Evaluation under Off-Nominal Condition 219

6.4.1 First-Come-First-Served (FCFS) 219

6.4.2 Schedule Departure Time (SDT) 241

6.4.3 Comparison of Operational Strategy under the Off-nominal Scenarios 256

6.5 Validation of Performance 261

6.5.1 Departure Delay Time 262

6.5.2 Delay Reason 264

6.5.3 Comparison 270

CHAPTER 7. Cost Evaluation 274

7.1 Number of Resources: Real Case 274

7.2 Schedule Variability Buffer: Robust Case 281

7.3 Cost Analysis 284

7.4 Summary 294

CHAPTER 8. Conclusion 295

8.1 Overview 295

8.1.1 Proposed Concept 298

8.2 Contribution 302

8.3 Summary 303

APPENDIX A. Description of Categories of Aircraft Turnaround Process 305
A.1 Passenger Handling 305
A.2 Luggage Handling 305
A.3 Cargo/Mail Handling 305
A.4 Aircraft Handling and Loading 306
A.5 Aircraft Ground Movement 307
A.6 Load Control 307
A.7 Airside Supervision and Safety 307

APPENDIX B. Flight Arrival Definition 309

APPENDIX C. Activity Phase And Resource Definition 310

APPENDIX D. Aircraft Model Definition 312

APPENDIX E. Turnaround Time and Schedule Variability Buffer Definition 315

APPENDIX F. Output Definition 316

APPENDIX G. Additional Experimental Results 318
G.1 FCFS- Busy, Weekday, and Nominal Weather 318
G.2 FCFS- Busy, Weekend, and Nominal Weather 319
G.3 FCFS- Normal, Weekday, and Nominal Weather 320
G.4 FCFS- Normal, Weekend, and Nominal Weather 321
G.5 SDT- Busy, Weekday, and Nominal Weather 322
G.6 SDT- Busy, Weekend, and Nominal Weather 323
G.7 SDT- Normal, Weekday, and Nominal Weather 324
G.8 SDT- Normal, Weekend, and Nominal Weather 326
G.9 SDT- Busy, Weekday, and Off-nominal Weather 327
G.10 SDT- Busy, Weekend, and Off-nominal Weather 328
G.11 SDT- Normal, Weekday, and Off-nominal Weather 329
G.12 SDT- Normal, Weekend, and Off-nominal Weather 330

REFERENCES 332

LIST OF TABLES

Table 1-1 National On-Time Performance (All Carriers, U.S. airport only) 4

Table 3-1 DOC+I Model [47][48] 44

Table 3-2 Suggested DOC+I Model for the Aircraft Turnaround Process 45

Table 3-3 Cost Minimization Model to Optimize the Schedule Variability Buffer 48

Table 4-1 Seasonal Delay in 2017 59

Table 4-2 Monthly Delay in 2017 62

Table 4-3 Daily Delay in 2017Daily Delay in 2017 66

Table 4-4 Flight Records on Tuesday in July 68

Table 4-5 Flight Records on Friday in July 71

Table 4-6 Flight Records on Tuesday in November 74

Table 4-7 Flight Records on Friday in November 77

Table 4-8 Popular Aircraft in the World [69] 82

Table 4-9 737 Family 83

Table 4-10 Boeing 777 Family Turnaround Activity Time 90

Table 4-11 Typical Time of Turnaround Process: Boeing 1 (Short) 98

Table 4-12 Typical Time of Turnaround Process: Boeing 2 (Medium) 99

Table 4-13 Typical Time of Turnaround Process: Boeing 3 (Long) 100

Table 4-14 Typical Time of Turnaround Process: Airbus 1 121

Table 4-15 Typical Time of Turnaround Process: Airbus 2 122

Table 4-16 Activity Summary 124

Table 4-17 Standard Format of Turnaround Activity 125

Table 4-18 Numerical Features of Aircraft Turnaround Time 126

Table 4-19 Refueling Time Chart 127

Table 4-20 Revised Typical Time of Turnaround Process: Boeing 1 (Short) 129

Table 4-21 Revised Typical Time of Turnaround Process: Boeing 2 (Medium) 130

Table 4-22 Revised Typical Time of Turnaround Process: Boeing 3 (Long) 131

Table 4-23 Revised Typical Time of Turnaround Process: Airbus 1 132

Table 4-24 Revised Typical Time of Turnaround Process: Airbus 2 133

Table 4-25 Revised Turnaround Time and Number of Passengers 134

Table 4-26 Different Cases for Scenario Analysis [78] 136

Table 5-1 Time Shift Period 151

Table 5-2 Atlanta Hartsfield-Jackson Airport: On-Time Performance (Major U.S. Carriers only, domestic [57]) 158

Table 5-3 Selected Aircraft Model for the Simulation Modeling 159

Table 5-4 Number of Delayed Flights due to the Weather and the Ratios 163

Table 5-5 Cumulative Delay Time due to the Weather and the Ratios 164

Table 6-1 Number of Resources on Time Shift 171

Table 6-2 Number of Resources for the Activity except Catering 174

Table 6-3 Number of Resources for Catering 174

Table 6-4 Minimum and Maximum of Early Arrival Time 179

Table 6-5 Statistics of Busy – Weekday with FCFS Strategy – Nominal Weather 188

Table 6-6 Statistics of Busy – Weekend with FCFS Strategy – Nominal Weather 191

Table 6-7 Statistics of Normal – Weekday with FCFS Strategy – Nominal Weather 194

Table 6-8 Statistics of Normal – Weekend with FCFS Strategy – Nominal Weather 197

Table 6-9 Performance of Simulator: Busy season (FCFS under Nominal Weather) 198

Table 6-10 Performance of Simulator: Normal season (FCFS under Nominal Weather) 199

Table 6-11 Statistics of Busy – Weekday with SDT Strategy – Nominal Weather 203

Table 6-12 Statistics of Busy – Weekend with SDT Strategy – Nominal Weather 205

Table 6-13 Statistics of Normal – Weekday with SDT Strategy – Nominal Weather 207

Table 6-14 Statistics of Normal – Weekday with SDT Strategy – Nominal Weather 209

Table 6-15 Performance of Simulator: Busy season (SDT under Nominal Weather) 210

Table 6-16 Performance of Simulator: Normal season (SDT under Nominal Weather) 211

Table 6-17 Number of Delayed Flights by Operational Strategy: Nominal Weather 217

Table 6-18 Total Delay Time by Operational Strategy 218

Table 6-19 Statistics of Busy – Weekday with FCFS Strategy – Off nominal Weather 223

Table 6-20 Statistics of Busy – Weekend with FCFS Strategy – Off nominal Weather 227

Table 6-21 Statistics of Normal – Weekend with FCFS Strategy – Off nominal Weather 231

Table 6-22 Statistics of Normal – Weekend with FCFS Strategy – Off nominal Weather 234

Table 6-23 Performance of Simulator: Busy season (FCFS under Off-nominal Weather) 236

Table 6-24 Performance of Simulator: Normal season (FCFS under Off-nominal Weather) 237

Table 6-25 Comparison of the Off-nominal and Nominal Scenarios' Performance: FCFS Strategy 238

Table 6-26 Comparison of the Off-nominal and Nominal Scenarios' Performance: FCFS Strategy 239

Table 6-27 Comparison of the Off-nominal and Nominal Scenarios' Performance: FCFS Strategy 240

Table 6-28 Statistics of Busy – Weekday with SDT Strategy – Off nominal Weather 243

Table 6-29 Statistics of Busy – Weekend with SDT Strategy – Off nominal Weather 245

Table 6-30 Statistics of Normal – Weekday with SDT Strategy – Off nominal Weather 247

Table 6-31 Statistics of Normal – Weekend with SDT Strategy – Off nominal Weather 249

Table 6-32 Performance of Simulator: Busy season (SDT under Nominal Weather) 251

Table 6-33 Performance of Simulator: Normal season (SDT under Nominal Weather) 252

Table 6-34 Comparison of the Off-nominal and Nominal Scenarios' Performance: SDT Strategy 253

Table 6-35 Comparison of the Off-nominal and Nominal Scenarios' Performance: SDT Strategy 254

Table 6-36 Comparison of the Off-nominal and Nominal Scenarios' Performance: SDT Strategy 255

Table 6-37 Number of Delayed Flights by Operational Strategy: Off-nominal Weather 259

Table 6-38 Total Delay Time by Operational Strategy: Off-nominal 259

Table 6-39 Comparison of the Operational Strategy's Performance: Off-nominal Scenario 260

Table 6-40 Statistical Analysis: All day 272

Table 6-41 Statistical Analysis: Evening 272

Table 7-1 Delay Time and Number of Delayed Flights by Number of Resources 278

Table 7-2 Delay Time and Number of Delayed Flights by Number of Resources 281

Table 7-3 Average Cost of Aircraft Block Time 286

Table 7-4 Delay Cost by the Schedule Variability 287

Table 7-5 Aircraft Model: Cost per Block Minute 289

Table 7-6 Overall System Cost with All Positive Delay Time 291

Table 7-7 Overall System Cost with the Delays ≥ 15minutes 293

Table 8-1 Comparison of Performance: SDT vs. FCFSComparison of Performance 301

Table B-1 Flight Arrival Definition 309

Table C-1 Activity and Resource Definition 310

Table D-1 Aircraft Model Definition 312

Table E-1 Turnaround Time and Schedule Variability Buffer Definition 315

Table F-1 Output Definition 316

LIST OF FIGURES

Figure 1-1 Delay Cause by Year [7] 3

Figure 1-2 Registered Delay Causes [9] 6

Figure 2-1 Ramp Layout for Servicing at B747SP [14] 15

Figure 2-2 Analysis of Current Turnaround Process 17

Figure 2-3 Stages of a Modeling and Simulation Study [19] 21

Figure 2-4 Relation between Arrival Delay and Departure Lateness [33] 26

Figure 3-1 Current Turnaround Process with the Stakeholders [26][34] 30

Figure 3-2 Definition of Research Scope 34

Figure 3-3 Authority of the Airline 35

Figure 3-4 Authority of the Airport 36

Figure 3-5 Hybrid Concept of the Authority 37

Figure 3-6 Whole Framework of Simulation 40

Figure 3-7 Aircraft Turnaround Process in Simulation 41

Figure 4-1 Data Analysis Process for Flight Arrival Scenarios 52

Figure 4-2 Objective on the Stage of Analysis 53

Figure 4-3 Data Analysis Process for Aircraft Turnaround 54

Figure 4-4 Distribution of Non-appointed Arrival in 2016 56

Figure 4-5 Distribution of Non-appointed Arrival in 2017 56

Figure 4-6 Seasonal Delay in 2017 58

Figure 4-7 Monthly Number of Arrived Flight and Delayed Flight in 2017 59

Figure 4-8 Monthly Total Delay Time in 2017 60

Figure 4-9 Monthly Delay Ratio in 2017 61

Figure 4-10 Daily Number of Arrived Flight and Delayed Flight in 2017 63

Figure 4-11 Daily Total Delay Time in 2017 64

Figure 4-12 Daily Delay Ratios in 2017 65

Figure 4-13 Type of Operational Scenarios 67

Figure 4-14 Flight Arrival on Tuesday, July 11, 2017 69

Figure 4-15 Flight Arrival on Tuesday, July 18, 2017 70

Figure 4-16 Flight Arrival on Tuesday, July 25, 2017 70

Figure 4-17 Flight Arrival on Friday, July 7, 2017 72

Figure 4-18 Flight Arrival on Friday, July 14, 2017 72

Figure 4-19 Flight Arrival on Friday, July 21, 2017 73

Figure 4-20 Flight Arrival on Friday, July 28, 2017 73

Figure 4-21 Flight Arrival on Tuesday, Nov 7, 2017 75

Figure 4-22 Flight Arrival on Tuesday, Nov 14, 2017 75

Figure 4-23 Flight Arrival on Tuesday, Nov 21, 2017 76

Figure 4-24 Flight Arrival on Tuesday, Nov 28, 2017 76

Figure 4-25 Flight Arrival on Friday, Nov 3, 2017 78

Figure 4-26 Flight Arrival on Friday, Nov 10, 2017 78

Figure 4-27 Flight Arrival on Friday, Nov 17, 2017 79

Figure 4-28 Operational Scenarios for Simulation Modeling 80

Figure 4-29 Turnaround Process of B737-600 [70] 84

Figure 4-30 Turnaround Process of B737-700 [70] 85

Figure 4-31 Turnaround Process of B737-800 [70] 86

Figure 4-32 Turnaround Process of B737-900 [70] 86

Figure 4-33 Servicing Arrangement of B777-200LR [71] 88

Figure 4-34 Turnaround Process of B777-200LR [71] 89

Figure 4-35 Turnaround Process of B777-300ER [71] 90

Figure 4-36 Turnaround Process of B787-8 [72] 93

Figure 4-37 Turnaround Process of B787-9 [72] 94

Figure 4-38 Turnaround Process of B787-10 [72] 95

Figure 4-39 Turnaround Process of B747-400ER [73] 96

Figure 4-40 Turnaround Process of B747-400, -400 Combi, and -400 Domestic[73] 97

Figure 4-41 Turnaround Process of A320 family [74] 102

Figure 4-42 Turnaround Process of A330-300 and A330-900 [75] 105

Figure 4-43 Turnaround Process of A330-200 and A330-800 [75] 107

Figure 4-44 Turnaround Process of A350-900 [76] 110

Figure 4-45 Turnaround Process of A350-1000 [76] 112

Figure 4-46 Turnaround Process of A380 (Main and Upper Deck) [77] 115

Figure 4-47 Turnaround Process of A380 (Main Deck) [77] 118

Figure 5-1 Positioning the Activities during Transit/ Turnaround [53] 139

Figure 5-2 Interdependency among the Turnaround Activities [26],[34] 140

Figure 5-3 Critical Path in Aircraft Turnaround [11],[60] 142

Figure 5-4 Simplified Work Structure for Discrete Event Simulation 145

Figure 5-5 Class Diagram of Entire Simulator 147

Figure 5-6 Class Diagram of Core 148

Figure 5-7 Class Diagram of Utilities 149

Figure 5-8 Summarized View for Experiments 165

Figure 6-1 Key Components of Experiments 168

Figure 6-2 Departure Delay Time Distributions (Case 1) 172

Figure 6-3 Departure Delay Time Distributions (Case 2) 172

Figure 6-4 Tracked Information of Activity Delay 173

Figure 6-5 Departure Delay Time Distributions (Case 3) 175

Figure 6-6 Departure Delay Time Distributions (Case 4) 176

Figure 6-7 Departure Delay Time Distributions (Case 5) 177

Figure 6-8 Tracked Early Arrival Time Distribution 180

Figure 6-9 Schedule Variability Buffer Time Value for the Largest Case by Aircraft Model 182

Figure 6-10 Departure Delay Distribution – FCFS, Busy, Weekday, Nominal Weather and Worst Resources 185

Figure 6-11 Departure Delay Distribution – FCFS, Busy, Weekday, Nominal Weather and Best Resources 187

Figure 6-12 Departure Delay Distribution – FCFS, Busy, Weekend, Nominal Weather and Worst Resources 189

Figure 6-13 Departure Delay Distribution – FCFS, Busy, Weekend, Nominal Weather and Best Resources 190

Figure 6-14 Departure Delay Distribution – FCFS, Normal, Weekday, Nominal Weather and Worst Resources 192

Figure 6-15 Departure Delay Distribution – FCFS, Normal, Weekday, Nominal Weather and Best Resources 193

Figure 6-16 Departure Delay Distribution – FCFS, Normal, Weekend, Nominal Weather and Worst Resources 195

Figure 6-17 Departure Delay Distribution – FCFS, Normal, Weekend, Nominal Weather and Best Resources 196

Figure 6-18 Departure Delay Distribution – SDT, Busy, Weekday, Nominal Weather and Worst Resources 202

Figure 6-19 Departure Delay Distribution – SDT, Busy, Weekend, Nominal Weather and Worst Resources 204

Figure 6-20 Departure Delay Distribution – SDT, Normal, Weekday, Nominal Weather and Worst Resources 206

Figure 6-21 Departure Delay Distribution – SDT, Normal, Weekend, Nominal Weather and Worst Resources 208

Figure 6-22 Departure Delay Distribution – Busy, Weekday, and Nominal Weather 214

Figure 6-23 Departure Delay Distribution – Busy, Weekend, and Nominal Weather 215

Figure 6-24 Departure Delay Distribution – Normal, Weekday, and Nominal Weather 215

Figure 6-25 Departure Delay Distribution – Normal, Weekend, and Nominal Weather 216

Figure 6-26 Departure Delay Distribution – FCFS, Busy, Weekday, Off-Nominal Weather, and Worst Resources 220

Figure 6-27 Departure Delay Distribution – FCFS, Busy, Weekday, Off-Nominal Weather, and Best Resources 222

Figure 6-28 Departure Delay Distribution – FCFS, Busy, Weekend, Off-Nominal Weather, and Worst Resources 225

Figure 6-29 Departure Delay Distribution – FCFS, Busy, Weekend, Off-Nominal Weather, and Best Resources 226

Figure 6-30 Departure Delay Distribution – FCFS, Normal, Weekday, Off-Nominal Weather, and Worst Resources 228

Figure 6-31 Departure Delay Distribution – FCFS, Normal, Weekday, Off-Nominal Weather, and Best Resources 230

Figure 6-32 Departure Delay Distribution – FCFS, Normal, Weekend, Off-Nominal Weather, and Worst Resources 232

Figure 6-33 Departure Delay Distribution – FCFS, Normal, Weekend, Off-Nominal Weather, and Best Resources 233

Figure 6-34 Departure Delay Distribution – SDT, Busy, Weekday, Off-Nominal Weather, and Worst Resources 242

Figure 6-35 Departure Delay Distribution – SDT, Busy, Weekend, Off-Nominal Weather, and Worst Resources 244

Figure 6-36 Departure Delay Distribution – SDT, Normal, Weekday, Off-Nominal Weather, and Worst Resources 246

Figure 6-37 Departure Delay Distribution – SDT, Normal, Weekend, Off-Nominal Weather, and Worst Resources 248

Figure 6-38 Departure Delay Distribution – Busy, Weekday, and Off-nominal Weather 256

Figure 6-39 Departure Delay Distribution – Busy, Weekend, and Off-nominal Weather 257

Figure 6-40 Departure Delay Distribution – Normal, Weekday, and Off-nominal Weather 257

Figure 6-41 Departure Delay Distribution – Normal, Weekend, and Off-nominal Weather 258

Figure 6-42 Departure Delay Time on Friday, July 07, 2017 262

Figure 6-43 Departure Delay Time on Friday, July 14, 2017 263

Figure 6-44 Departure Delay Time on Friday, July 14, 2017 263

Figure 6-45 Departure Delay Time on Friday, July 28, 2017 264

Figure 6-46 Delay Reason Analysis on Friday, July 07, 2017 265

Figure 6-47 Delay Reason Analysis on Friday, July 14, 2017 266

Figure 6-48 Delay Reason Analysis on Friday, July 21, 2017 266

Figure 6-49 Delay Reason Analysis on Friday, July 28, 2017 267

Figure 6-50 Selected Delay Reason on Friday, July 07, 2017 268

Figure 6-51 Selected Delay Reason on Friday, July 14, 2017 268

Figure 6-52 Selected Delay Reason on Friday, July 21, 2017 269

Figure 6-53 Selected Delay Reason on Friday, July 28, 2017 269

Figure 6-54 Distribution of Number of Flights: All Day 270

Figure 6-55 Distribution of Number of Flights: Evening 271

Figure 7-1 Departure Delay Distribution by the Number of Resources from 30 to 60 275

Figure 7-2 Total Delay Time by the Number of Resources 276

Figure 7-3 Number of Delayed Flights by the Number of Resources 277

Figure 7-4 Departure Delay Distribution by the Number of Resources from 44 to 51 279

Figure 7-5 Delay Analysis by the Number of Resources from 44 to 51 280

Figure 7-6 Schedule Variability Buffer: Ideal, Largest and Robust Cases 282

Figure 7-7 Candidate of Robust Schedule Variability Buffer 283

Figure 7-8 Delay Evaluation by the Schedule Variability Buffer 284

Figure 7-9 Cost Distribution: All Positive Delay Time 290

Figure 7-10 Cost Distribution: Delay Time > 15 minutes 292

Figure 8-1 Role of Automated Cost-Efficient Decision-Making System 299

Figure 8-2 Modeling Structure of Integrated Turnaround System 300

Figure G-1 Departure Delay Distribution – FCFS, Busy, Weekday, Nominal Weather and Best Resources 318

Figure G-2 Departure Delay Distribution – FCFS, Busy, Weekend, Nominal Weather and Best Resources 319

Figure G-3 Departure Delay Distribution – FCFS, Normal, Weekday, Nominal Weather and Best Resources 320

Figure G-4 Departure Delay Distribution – FCFS, Normal, Weekend, Nominal Weather and Best Resources 321

Figure G-5 Departure Delay Distribution – SDT, Busy, Weekday, Nominal Weather and Best Resources 322

Figure G-6 Departure Delay Distribution – SDT, Busy, Weekend, Nominal Weather and Best Resources 323

Figure G-7 Departure Delay Distribution – SDT, Normal, Weekday, Nominal Weather and Best Resources 325

Figure G-8 Departure Delay Distribution – SDT, Normal, Weekend, Nominal Weather and Best Resources 326

Figure G-9 Departure Delay Distribution – SDT, Busy, Weekday, Off-Nominal Weather, and Best Resources 327

Figure G-10 Departure Delay Distribution – SDT, Busy, Weekend, Off-Nominal Weather, and Best Resources 328

Figure G-11 Departure Delay Distribution – SDT, Normal, Weekday, Off-Nominal Weather, and Best Resources 329

Figure G-12 Departure Delay Distribution – SDT, Normal, Weekend, Off-Nominal Weather, and Best Resources 331

SUMMARY

Air transportation is a growing sector with increasing consumer demands. Airports have become congested in the global air transport system due to high growth in demand for air travel. Improving the capacity of the air transportation system is almost impossible because of space and cost limitations. Thus, a more efficient operational strategy is necessary to handle the increased traffic with current facilities.

From the airline’s perspective, inherent delay uncertainty has an adverse effect on their customers. However, airlines recognize the saturation of airports, a factor that is not under their control [88]. Thus, airlines ought to attempt to ensure punctuality in the operation of ground handling to improve their service quality “On-time performance”.

Although the ground handling process has significant impacts, it has not taken center stage in past and current research. Ground handling has an essential role in the recovery from past delays either aggravating or alleviating the problem.

To alleviate the delay and emphasize the time efficiency of ground operations, the airlines could consider an innovative operational framework. The research work presented in the current dissertation has captured that the ground processes are an essential cause of departure delay and has explored strategies for improvement in the aircraft turnaround process such that little to no investment from the airlines would be required.

The aim of the research focuses on improving the aircraft turnaround process with current capacity. The aircraft turnaround process is a complex process that associated with multiple stakeholders and influenced by their actions. The critical improvement concept

presented is the integration of work procedures including all stakeholders and management of relevant resources.

When considering the vast and complex airport environment, Discrete Event Simulation (DES) can be a suitable modeling solution. Airports, and specifically the turnaround process, are, therefore, ideally suitable for the application of such simulations because of their stochastic and dynamic characteristics [45].

For reliable simulation modeling, the required inputs for the integration of the turnaround process within current physical capacity are defined. Thus, the historical flight data has been analyzed, and all turnaround activities and their time for the selected aircraft models have been discussed.

A simulation of the turnaround process was created employing the input data and capturing multiple operational scenarios. It obeys a critical path by the sequence and dependency of the ground activities. In order to test the hypotheses, the simulator was set up as the apparatus for hypothesis testing. The tracked metrics for delays and their impact are analyzed in the context of proving/disproving the previously stated hypotheses.

The performance of the simulator proves the hypotheses and shows their reliability. Thus, based on the result, it calculates the direct operating cost under different scenarios. However, only the variables relevant to the turnaround process directly are evaluated. Even with limited access to the data, the relevant variables are successfully tracked in the cost calculation process. The minimal cost of the overall system is captured and indicates the dominant elements to reduce the total cost. This cost reduction, achievable thanks to the

“What-if” capabilities of the simulations, will be the incentive required to encourage airlines into a symbiotic turnaround environment producing more stable schedules.

CHAPTER 1. INTRODUCTION

Air transportation is a growing sector with increasing consumer demands. Airports have become congested in the global air transport system due to high growth in demand for air travel. Currently, there is a limitation for the capacity of the air transportation system because of the airport capacity in the United States [1].

Thus, it can be assumed that delays in the global air transport system cause congestion in the airspace and delay airport flight operations. In order to handle the high volume of demand while meeting safety and punctuality requirements a more efficient operational strategy is needed to handle the increased traffic with current facilities.

Lack of on-time performance due to significant flight delays is recognized as one of the main obstacles to the steady growth in meeting air traffic demand [2]. Inherent delay uncertainty has an adverse effect on the stakeholders who manage fleets, crews, and passengers. Additionally, there would be financial and environmental inefficiencies if congest airports have an increased congestion [3].

Unexpected delays affect an airline’s market share because the unexpected delays impact the passengers’ comfort level. If passengers experience delays in airlines, they are inclined to change their flight selection more in comparison to ones who did not [4]. Thus, delays can be regarded as an indicator of low customer satisfaction level and inefficient scheduling.

Although airlines generally compete on the offered fares, it is common knowledge that a flight’s on-time performance is a key indicator of airline service quality, which drives customer satisfaction and loyalty [5]. On the other hand, airlines do not have the capability to increase airport capacity or airspace in order to increase flight on-time performance. Thus, to ensure punctuality, airlines are forced to explore improvements to operational strategy, in lieu of physical space expansion.

Airlines have been reporting not only on-time data but also the causes of delays and cancellations to the Bureau of Transportation Statistics since June 2003, thus explaining the factors leading to flight delays. There are five broad categories [6] that were created by the Air Carrier On-Time Reporting Advisory Committee as followings:

- Air Carrier

  "The cause of the cancellation or delay was due to circumstances within the airline's control. Crew problems or ground activities are under this category."[1]
- Extreme Weather

  "Significant meteorological conditions (actual or forecasted) that in the judgment of the carrier delay or prevents the operation of a flight such as a tornado, blizzard or hurricane." [1]
- National Aviation System (NAS)

  "Delays and cancellations attributable to the national aviation system that refers to a broad set of conditions, such as non-extreme weather conditions, airport operations, heavy traffic volume, and air traffic control." [1]
- Late-arriving aircraft

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[1] Unites States Department of Transportation, Bureau of Transportation Statistics, Airline On-Time Statistics and Delay Causes

"A previous flight with the same aircraft arrived late, causing the present flight to depart late." [1]

- Security

"Delays or cancellations caused by the evacuation of a terminal or concourse, re-boarding of aircraft because of a security breach, inoperative screening equipment and/or long lines in excess of 29 minutes at screening areas." [1]

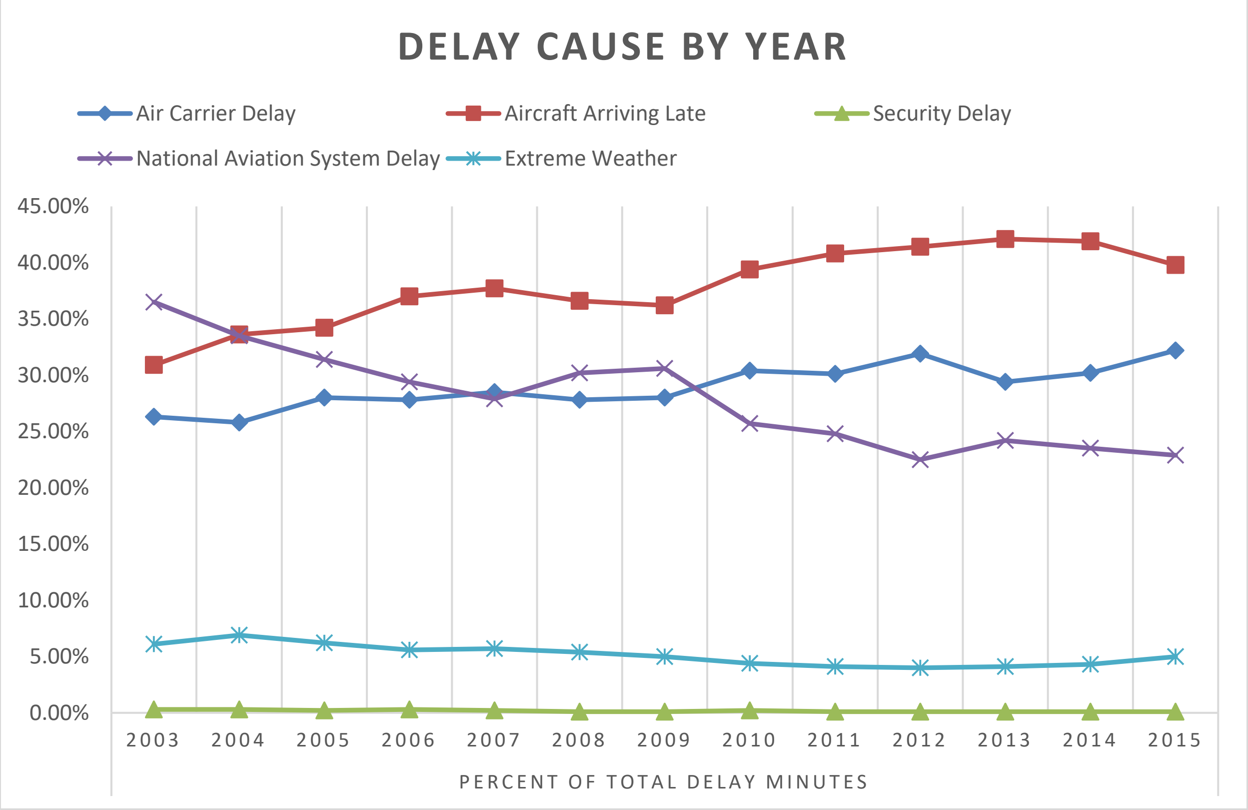


Figure 1-1 Delay Cause by Year [7]

Figure 1-1 shows the percentage of each category in terms of total delay minutes. In the recent years, it is evident from Figure 1-1 that late-arriving aircraft are the most frequent cause for delays. Another interesting trend is the increase in both aircraft arriving late and air carrier delay in contrast to the decrease in the NAS delay suggesting the necessity for airlines to look for improvements in these categories.

1.1 Motivation

1.1.1 Increasing Delay

The Federal Aviation Administration (FAA) describes delayed flights as those that either arrive 15 minutes or more past their respective scheduled times. In other words, it could be recorded as an on-time flight, if the flight is 14 minutes (or less) late at the time of departure.

Table 1-1 National On-Time Performance (All Carriers, U.S. airport only)

% on time	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Departure	80.96	82.44	79.19	77.31	80.32	81.88
Arrival	79.62	81.85	78.34	76.25	79.92	81.42
% delayed						
Departure	17.13	16.27	19.30	20.50	18.14	16.95
Arrival	18.24	16.65	19.93	21.32	18.28	17.16
Average delay time (min)						
Total	56.53	56.84	56.82	57.23	59.48	62.46
% canceled						
Total	2.45	1.15	1.59	2.65	1.85	1.35

Ref: Bureau of Transportation Statistics, Summary data for U.S. Flights only.

The statistics in table 1-1 show that in the year 2015, out of a total of 5,819,079 flights there were 4,650,569 on-time operations and 1,063,440 delayed operations. It indicates that there were 81.42 percent of operations on-time and 17.16 percent of operations with delayed performance. Furthermore, the average time of delay for domestic flights in the US in 2016 was 62.46 minutes, which has been on the rise since 2011, prompting the need to address delays directly.

1.1.2 Cause of Delay

Reasons for flight delays can be allocated to six main categories [9] (a type of reason):

- Rotation

  Delayed flight cycles
- ATFM/ATC

  Restrictions according to crowed ATC sectors, traffic flow restrictions
- Airport Authorities

  Problems due to runway capacities, occupied parking positions, etc.
- Handling

  Delayed ground processes
- Technical

  Malfunction of technical systems
- Weather

  Negative weather influences

These six categories cover up to 85% of potential flight delays. The aircraft turnaround process that contains ground handling management is under the category ‘Handling’ and accounts for 10% of delays. (See figure 1-2)

The aircraft turnaround process will always be a complex operation due to the number of steps and relevant stakeholders. Figure 1-2 shows the percentages of significant delay causes.

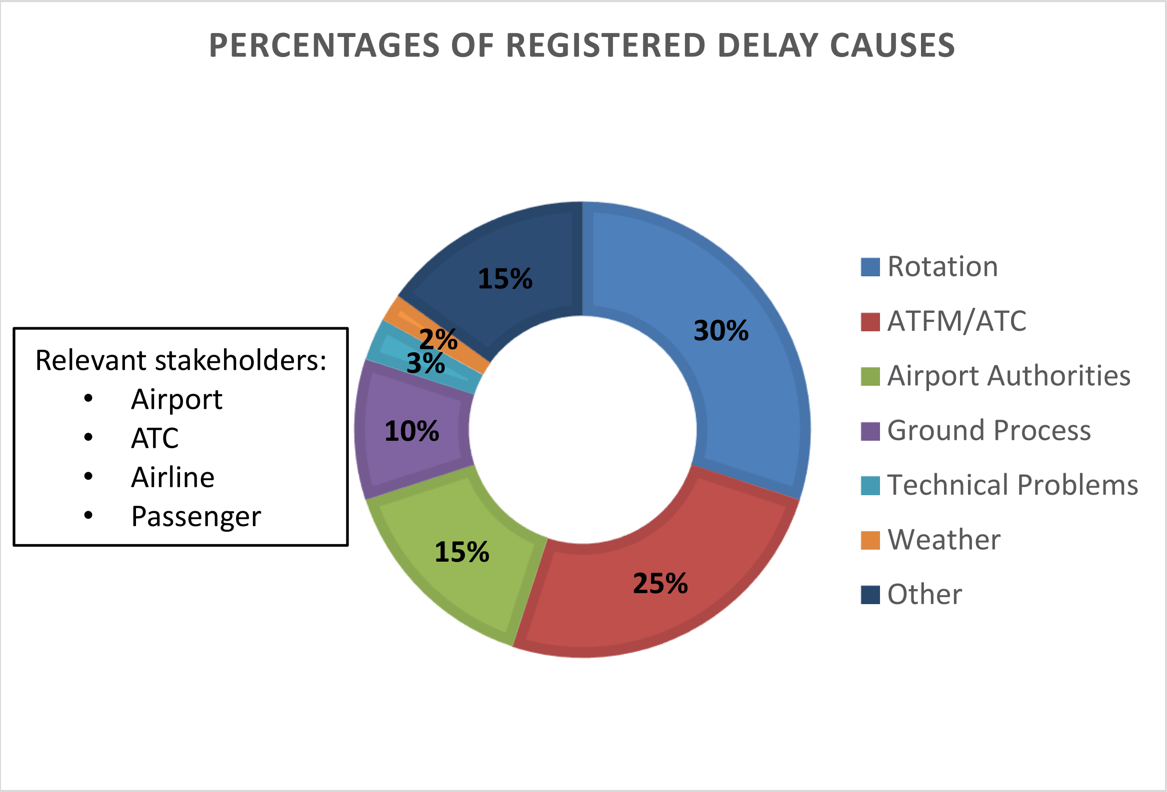


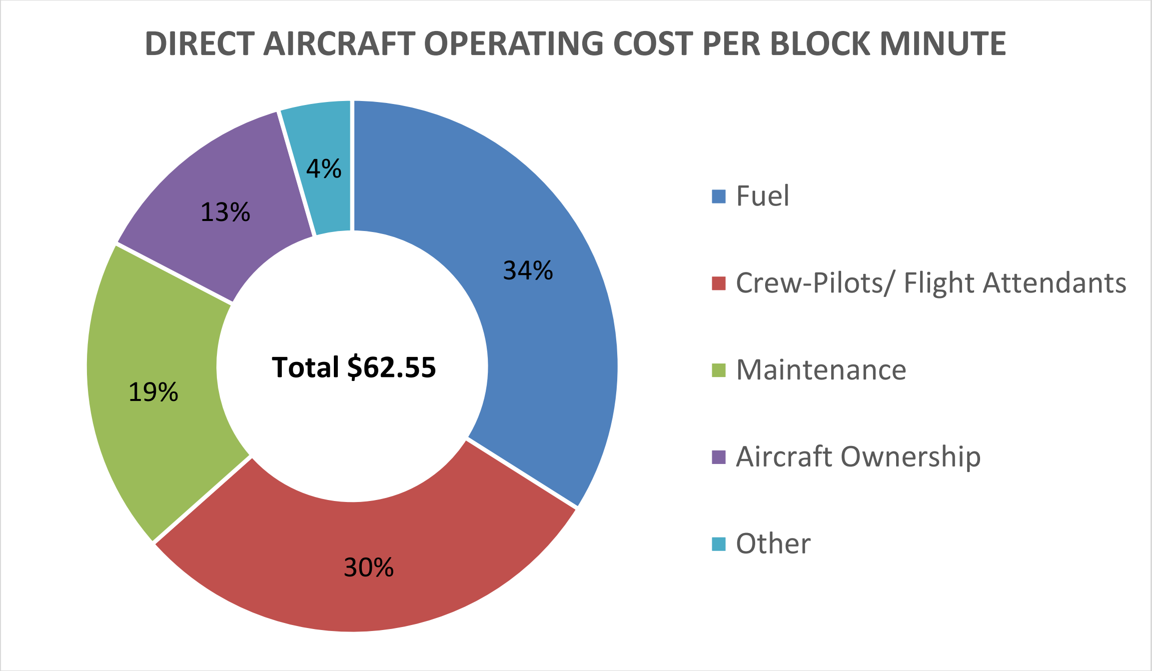
Figure 1-2 Registered Delay Causes [9]

The delayed ground processes are an essential cause of departure delay, impacting departure delay by 10 percent. They can also play a critical role in the recovery from previously accumulated delays either aggravating or alleviating the problem. However, ground processes have not taken center stage in past and current research. Eurocontrol announced the recent concept of collaborative decision making for airports but did not include in detail the analysis of the ground handling process [10].

In the past, each airline has performed the ground handling services by themselves. However, they started ‘unbundling’ the ground activities with deregulation because of the need to be more cost-conscious [11]. It was an attempt to co-operate those activities with the specialist companies to reduce the cost. Current trends involve the outsourcing of ground handling activities to specialized companies. In other words, there are a large variety of stakeholders involved in ground handling operations given the abundance of airports around the world. There are various ways to deal with each ground handling process by multiple stakeholders.

1.1.3 Delay Handling Cost

The flight delay partly affects the Direct Operating Cost (DOC). The departure delays require that more cost be paid by airlines. According to the organization of airlines for America, the per-minute cost of delays to U.S. Airlines was $62.55 in 2016 [83]. Figure 1-3 shows the detailed component for per-minute cost of delays. . The cost was estimated for only DOC, not including indirect operating cost and non-operating cost which implies that the actual cost resulting from delays would be higher than $62.55. In order to reduce expenses on DOC, it is required to determine a quantified value of how much an airline can save from the turnaround process.



Ref. The organization of Airlines for America: DOT Form 41 data for U.S. scheduled passenger airlines

Figure 1-3 Per-minute Cost of Delays to U.S. Airlines in 2016

It is important to note that delayed flight cycles impact the aircraft turnaround process. Thus, any model of the aircraft departure delay should consider the disruption of ground operations by the late arrivals [8]. Therefore, it is essential to investigate the relationship between uncertainty in the arrival schedule of an aircraft and its turnaround process.

1.2 Research Objective

Ground process not only serves as a critical sub-system of airline and airport operations, but also acts as an important role in customer satisfaction [11]. The operations of ground handling are carried out simultaneously to reduce the time spent on the ground and to raise the aircraft productivity. The inherent and experienced delays have an essential impact on efficiency, from the view of the airlines. Therefore, the airlines emphasize the time efficiency of ground operations.

The objective of the research, therefore, is twofold: first, to improve the aircraft turnaround process with current capacity, and second, to monitor the total cost as a trade-off between delay costs and scheduling time costs.

Primary Research Objective
Develop an approach to provide a stable operational turnaround process with the current capacity

In this respect, the primary objective of this dissertation is to develop a stable operational approach to the aircraft turnaround process with current capacity and to show cost modeling based on the suggested method. The development methods is then demonstrated on an airport in the United States thus validating the developed capabilities

CHAPTER 2. BACKGROUND

Chapter 1 summarizes the state of the aircraft turnaround process. Arguments provided indicate that both the average time and the handling cost of delay has seen an increase over the past few years. On-time performance is a critical factor by which passengers judge the service quality of an airline.

Airlines recognize the saturation of airports, a factor that is not under their control [88]. Instead, airlines ought to attempt to ensure punctuality in the operational area to improve their service quality "On-time performance."

The research work presented in the current dissertation has captured that the ground processes are an essential cause of departure delay and has explored strategies for improvement in the aircraft turnaround process such that little to no investment from the airlines would be required. This investigation is summarized as the primary objective guiding the research work, given as: "***The development of an approach to provide a stable operational turnaround process with current capacity.***" To achieve the primary goal, a set of research questions are formulated, with the first related to measuring stability being:

Research Question 1
How to assess stability for the operation of the turnaround process?

Stability can be defined as the ability to deal with uncertainty under disruption in this research work. In other words, stable system should show the less sensitivity to uncertainty. Thus, two metrics are considered to assess stability: the number of on-time flights and the total delay time. The number of on-time flights and the delay time can in turn explain the punctuality of an aircraft.

The article on the Washington Post pointed out the airlines and airports ranked highest for punctuality. Since punctuality is a key performance indicator and marketing tool in the travel industry, especially for commercial flights, each time a flight is delayed — or worse, canceled — airlines and airports lose customer loyalty [67]. Losing customer loyalty means to lose the airlines' profit. Furthermore, delays lead to major amount of the additional expense. It was mentioned in section 1.1.3 that the per-minute direct cost of delays to U.S. Airlines was $62.55 in 2016. Thus, the yearly delay cost incurred by airlines would be billions of dollars if the indirect cost including the passenger compensation were to be considered [83].

Therefore, the number of on-time flights and the delay time would be a proper metric to assess the stability for the operation of the turnaround process. The hypothesis associated with this observation is formally stated as:

Hypothesis 1

If the two metrics (the number of on-time flights and the delay time) are tracked along their associated uncertainty, then the stability of the turnaround process can be assessed.

Based on the FAA description of delay, a flight is counted to towards the set of "on-time" flights if the flight is ready for departure within 15 minutes of its scheduled departure time.

The following shows the definition of on-time flight and delayed flight to support Hypothesis 1:

- On-time flight:

  The time of ready to departure $<$ the scheduled departure time + 15 minutes
- Delayed flight:

  The time of ready to departure $\geq$ the scheduled departure time + 15 minutes

2.1 Aircraft Turnaround Process at Airports

2.1.1 Definition of Aircraft Turnaround Process

The aircraft turnaround process can be defined as including all ground handling activities that should be completed for an aircraft while parked at a terminal gate. Here, the ground handling represents the series of activities that are required to separate an aircraft from its load, which means the passenger, luggage, cargo, and mail on arrival at an airport, and reloading before the next departure [13].

The ground handling process comprises very diverse tasks between the time of arrival of an aircraft at the gate and that of its departure. It consists of all passenger, luggage, cargo, and aircraft-related processes, and includes all personnel activities. During that time, the aircraft is prepared for the next flight, and some operations such as passenger de-boarding and boarding, luggage unloading and loading, refueling, cleaning, catering, water supplying, power supplying and maintenance checks must be completed.

2.1.2 Definition of Aircraft Turnaround Process Time

As the stability of the turnaround process is defined in terms of the total delay time, it is essential to first describe a means to estimate the total delay time. This is due to the relationships between the delay time and the turnaround process time.

Research Question 1-1

How to model the delay time?

The total delay time is modeled as a function of the scheduled time of departure, the scheduled time of arrival, and the scheduled turnaround time of the turnaround aircraft where the schedule departure time is defined as the sum of the scheduled time of arrival and the scheduled turnaround time of the turnaround aircraft.

The turnaround time of the aircraft can be defined as the period that the aircraft occupies a gate at the airport. Every aircraft has a minimum characteristic turnaround time, that varies by the aircraft type. In general, a larger aircraft requires a longer time. Even though the airlines operate the same type of aircraft, the turnaround time can be different due to the number of services provided by each airline. If the airline provides more services, it takes a longer time to complete the turnaround process. Aircraft turnaround time largely rides on the number of processes and its complexity.

The scheduled turnaround time has two parts: the buffer time and the ground time of turnaround aircraft. The role of the schedule variability buffer is to absorb arrival delays and unexpected delays resulting from ground handling process [33].

With the above observations and definitions, the total delay time is hypothesized to be:

Hypothesis 1-1.

If the schedule variability buffer and the accurate time for the turnaround process are obtained, then the total delay time can be predicted.

$$\text{Total delay time} = \max(0, RTD - STD)$$

$$STD = STA + T_{ST} = STA + T_G + T_{var}$$

$$T_{ST} = T_G + T_{var}$$

$T_{ST} =$ Scheduled turnaround time of the aircraft

$T_{var} =$ Schedule variability buffer time of the aircraft

$T_G =$ Ground time of the aircraft

$STA =$ Scheduled arrival time of the aircraft

$STD =$ Scheduled departure time of the aircraft

$RTD =$ Real time of departure of the aircraft

2.1.3 Categories of Aircraft Turnaround Process

The general definition of the aircraft turnaround process is described in section 2.1.1, and the time for the turnaround process is explained in section 2.1.2. Reviewing the detailed activities by categories in the turnaround process is necessary to figure out the turnaround process. In this section, the most used list of turnaround processes is stated below by flight operation status. Figure 2-1 shows an example of ramp layout illustrating the apron positions typically designated for servicing and loading equipment for a Boeing 747. The categories of aircraft turnaround process are illustrated in detail in Appendix A.

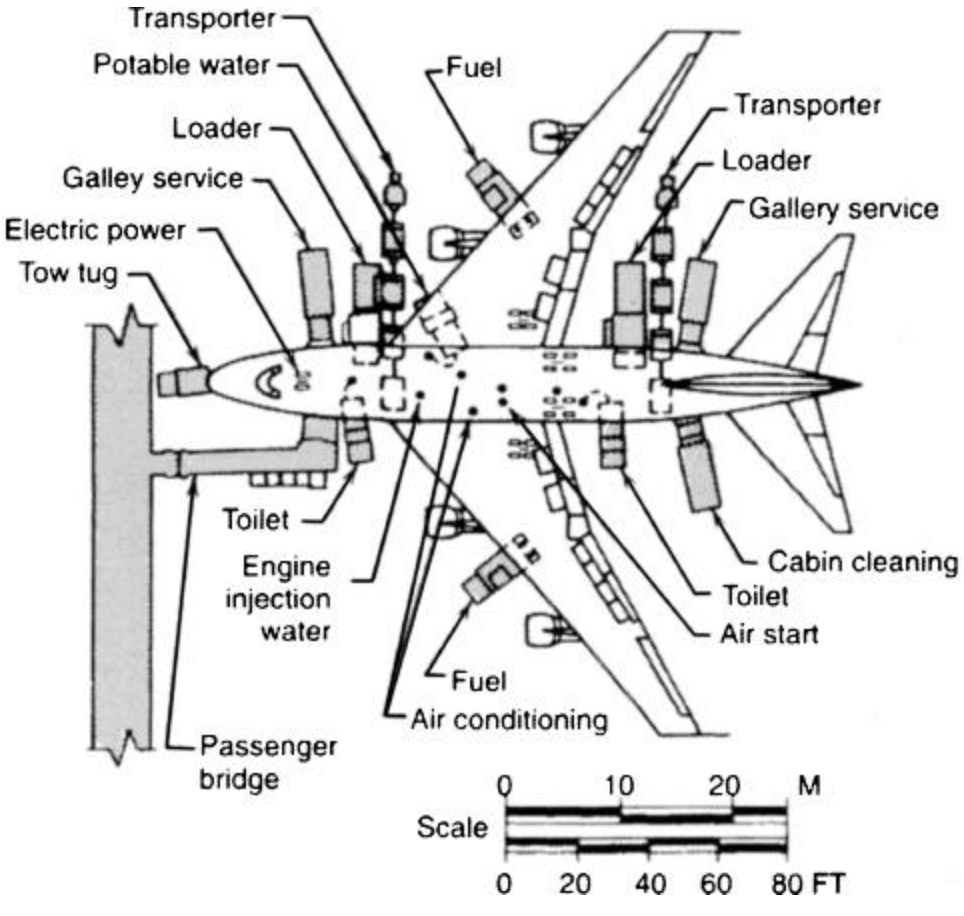


Figure 2-1 Ramp Layout for Servicing at B747SP [14]

- After arrival
    - Placing of chocks (rubber blocks that prevent aircraft from moving) in front of the aircraft's wheels after it comes to a full stop [9]
    - De-boarding of passengers and crew
    - Unloading of luggage and cargo
    - Security
- Before departure
    - Cleaning
    - Fueling
    - Catering
    - Luggage and cargo loading
    - Passenger boarding
    - Security
    - Aircraft check
    - Removal of chocks for departure

2.2 Analysis of the Current Aircraft Turnaround Process

It is essential to understand the current aircraft turnaround process in order to portray the system accurately. A thorough understanding of the current state of the system helps to identify problems and define potential areas of improvement.

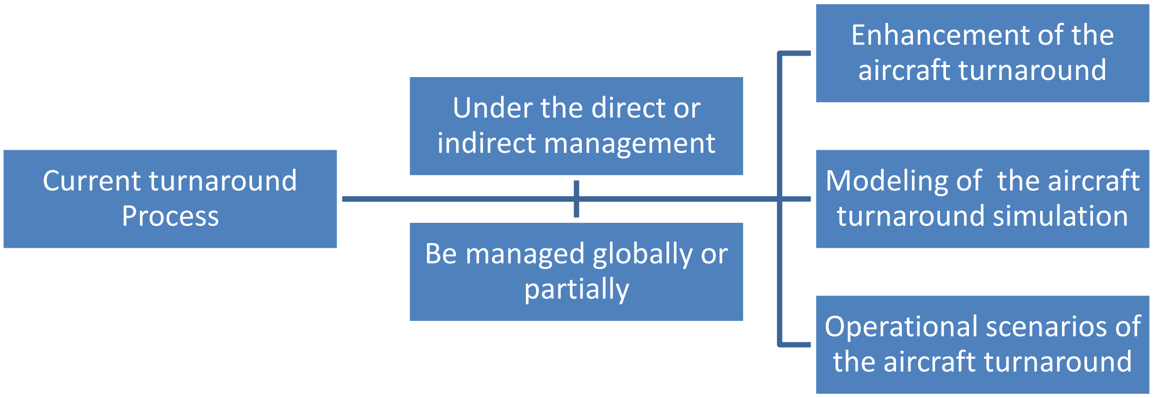


Figure 2-2 Analysis of Current Turnaround Process

Schematically, the research work applies modeling and simulation techniques to provide a stable operational turnaround process. The focus of the approach can be divided into three groups: enhancement of the aircraft turnaround process, modeling of the aircraft turnaround process, and operational scenarios of the aircraft turnaround process. Thus, the following sections present a review and analysis of their current state.

2.2.1 Enhancement of the Aircraft Turnaround Process

According to research regarding airport surface operations [15], airport surface is key element of the air transport system. The surface serves as the bridge between ground and air and facilitates the ground movements of vehicle. The proposed framework is a holistic risk assessment of airport surface operations that integrates the actions of all relevant stakeholders. The main role of the framework is supporting the management of change, training and safety communication. The notable point of [15] is an attempt to integrate the actions of all relevant stakeholders, in contrast to the current approach to surface safety management which is fragmented. A view of the whole airport surface operations and its integration was attempted in the published work.

The aircraft turnaround process which is covered by this research is related to multiple stakeholders and influenced by the actions of the stakeholders. Thus, as discussed in detail in Chapter 3, the current research addresses the key topic of integration of the actions of all relevant stakeholders.

The research work [15] focuses on the integration of the actions by all relevant stakeholders. The integration of activities is realized by having the stakeholders finish on time.

The benefits of integration and standardization of specific activities in the ground handling process is noted in the Vanguard article [16] where airports are shown to have their own unique approaches to refueling. The article proposed a general framework of refueling to which any airport, airline, or specialized provider can follow. A solution combining technology with clearly understood processes [17] is suggested. The standardization and integration of the refueling procedure is an excellent point to create a standard format that can support training and auditing regarding the elimination of incidents.

The article indicates that refueling is closely related to safety and is impacted by volume of traffic, and hence is a needs for an improvement to the process through integration and standardization. However, the other activities in the ground handling process are also impacted by the volume of traffic, and safety should be given priority.

Thus, the current research work looks at the integration and standardization of all ground handling procedures, and not just the refueling activity.

The benefits of integration and standardization of the refueling procedure in the ground handling process are further explored in [16]. When looking at the procedure of refueling, the identification of fuel truck or fuel pumps the integration of resources and equipment is enabled. In general, the integrated work procedure might cause the resources and equipment to be shared by the stakeholders.

The paper [18] discusses airport operational performance issues. Based on [18], the following factors will be considered for optimization of ground resources and the corresponding design factors will be applied in the models as follows:

- Efficient management of shared resources
- Improved tracking system of ground resources
- Real-time monitoring for ground handling disruptions
- Consolidated information transfer system from all stakeholders to the dispatchers

There are two notable points: the strategy of sharing ground resources and real-time monitoring of the turnaround process by managing disruptions. We can use the former as one of modeling assumption in order to proceed the integrated approach: all resources and equipment are shared by all stakeholders which means that if there are any resources available, any aircraft can request and receive the necessary ground handling service.

The most recent research relevant to simulation of the ground handling process is focused on the improvement of the ground handling process and reduce delay time and cost. However, in contrast to the current research work, it focused on the simulation of the ground handling process in a piecemeal fashion.

2.2.2 Modeling of the Aircraft Turnaround Process

Modeling and simulation techniques have an advantage in various ways. They can study the behavior of a system without building it, perform “What-If” analysis quickly, and help to find un-expected phenomena and behavior of the system.

An overview of a modeling and simulation study is illustrated in Figure 2-3. In the construction of the conceptual model, problem and expected performance should be stated clearly, because the conceptual model is comprehensive regarding a specification for developing the simulation program [19].

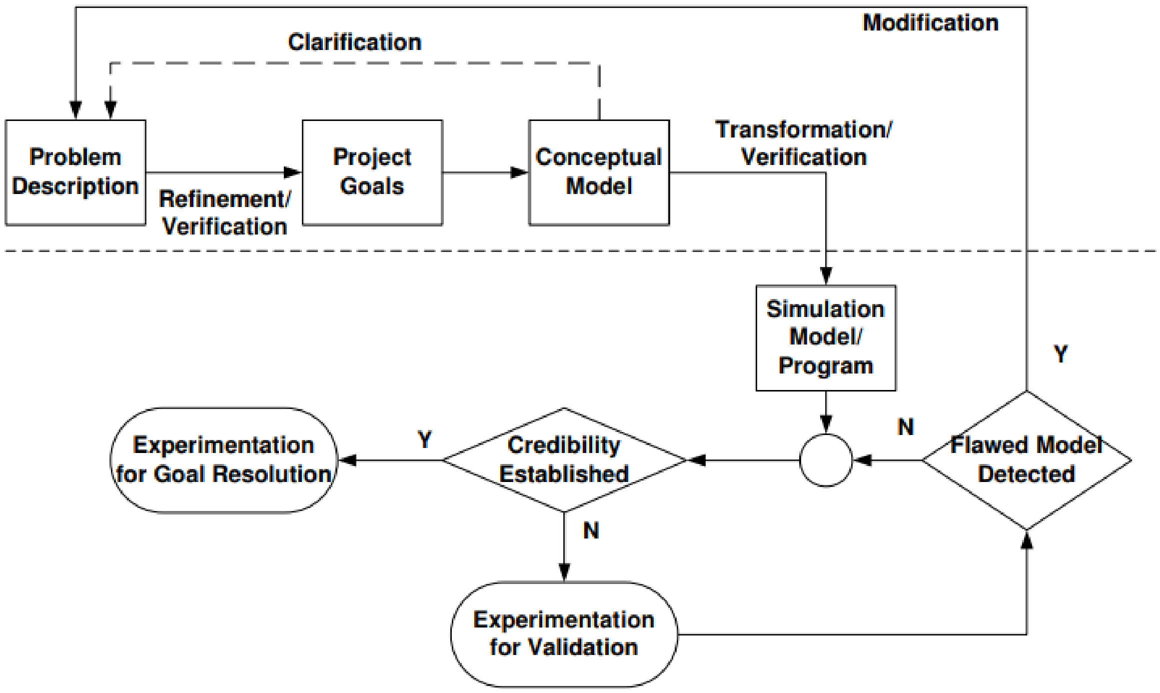


Figure 2-3 Stages of a Modeling and Simulation Study [19]

There is previous research considering the enhancement of simulation capabilities for aircraft ground handling [21]. The research mainly focuses on the advances made in the field of aircraft ground handling simulation and guides simulation engineers in using these improvements to meet their individual requirements. It addressed the detailed essential requirements and assumptions that would be helpful for aircraft ground handling simulation. It represents that conceptual modeling is a crucial step for reliable simulation.

The process of simulation modeling necessitates the comparison of the various methods and the selection of the best solution in order to simulate the aircraft turnaround process. Aircraft turnaround process modeling has been studied many times in previous literature by utilizing different methodologies [22]; mainly simulation, integer programming, dynamic programming, heuristics, petri-nets, and fuzzy models.

The research by Andersson [23] applied Integer programming into airport operations. The integer programming model tries to include the decision making process of airlines in aircraft turnaround process.

It describes building accurate and straightforward models of hub airports in order to capture airport dynamics. Furthermore, it shows quantitative evaluation for airport operation with two simple queuing models, which were created to simulate the taxi-in and taxi-out processes [23]. The remarkable point is dividing the aircraft turnaround process into the simple small models and combining the smaller pieces, because of complexity.

A research paper shows the application of Agent-Based Modeling (ABM) into airport operations [24]. It simulates the Hong Kong International Airport and selected aircraft ground services provided by China Aircraft Services Limited to improve the services and minimize the cost. It shows an example with the maintenance activity: optimize the number of maintenance resources with respect to minimize the delay and operating cost. Based on the latest version of the book 'Simulation Modeling and Analysis' by Averill Law, the conclusion was that ABM is just a particular case of Discrete Event Simulation (DES) [25]. Thus, DES is considered one of the possible methods regarding broad categories.

Sara Sanz de Vicente published the master study of ground handling simulation. [26] It analyzed the ground handling process and applied Comprehensive Airport Simulation Technology (CAST) Ground Handling program which can create a 3D simulation and include the process cost analysis. It shows a simulation of ground handling for the Airbus A320. The excellent point of [26] is finding a critical path and scheduling the turnaround operations. However, the CAST simulation model which is used to find efficient ground handling based on the current state, thus it would have been better to introduce a new simulation model which schedules the turnaround operations, finding the bottleneck operations by considering resource limitations [22]. The next excellent point is using the information of commercially available aircraft. However, it ignores that there are various types of aircraft that are operated at the airport. Thus, the ones that are most frequently used are chosen for the analyses and their information used.

Norin et al., implemented a simulation for logistical turnaround operations with an optimization model for a de-icing vehicle scheduling model [27]. The primary goal of the research is to examine the possibility of the identification of improved airport logistics for the overall performance by optimizing the de-icing operation belonging to the turnaround. After optimizing the de-icing process and integrating the model to the simulation, the efficiency has been compared between four different scenarios. This study proposed a different way of approaching the increase on the performance of overall aircraft turnaround activities by suggesting the scheduling of each operation independently and combining them in one simulation model to improve the efficiency. However, passenger embarking/disembarking from 1-2 doors or parking position of the aircraft, essential components of ground management, are not considered in the model.

Another aspect of the turnaround modeling has been studied by Kunze, Oreschko, and Fricke [28]. A Monte Carlo Simulation has been utilized to model the turnaround operations to calculate the stochasticity of turnaround operations. This study shows the importance of the information flow in the turnaround time with buffer time by introducing the sensor technology or checkpoints. However, the study fails to consider the ground handling resources such as personnel. It would have been a more accurate model if the resource constraints were added to the model.

Another work presents a stochastic programming model developed to schedule aircraft ground operations [29]. The mathematical model has been written as a multi-agent project scheduling problem within uncertainty. The scenarios which are conducted in a real environment showed that the uncertainties of the turnaround activities are being taken into consideration by the model and converge to a steady state. Because we cannot expect the future situation, so considering uncertainty is a good point. However, the mathematical model was developed from a job shop scheduling perspective. Thus the solution time of the problem is considerable and reaching the optimal solution is not possible. Integrating the agents' decision to the problem, however, is an excellent approach to the turnaround scheduling problem.

Trabelsi et al. had developed an online decentralized management structure using fuzzy formalism. The objective of the decentralized multi-fleet management problem is to minimize the ground handling variable costs and minimize the travel distance between airport fleet involved in the ground handling while assigning each ground handling vehicles to the aircraft [30]. Different scenarios were considered since there are different types of fleet in the airport at the same time. It is a good point because it reflects a realistic environment. However, the model was more focused on the airport side rather than the airline.

Vidosavljević used petri-nets for development of an aircraft turnaround model. The model shows the aircraft turnaround by including air-bridge positioning, passengers deboarding/boarding, portable water, catering, cleaning, luggage loading/unloading and fueling [31]. It used the critical path method to detect the operations which are in the critical path, and it is a useful source from the view of this thesis.

The application of various modeling techniques about aircraft turnaround process has been discussed, and the pros and cons of each approach are identified. Here is the list of methods:

- Agent-based modeling
- Discrete event simulation
- Integer programming
- Monte Carlo simulation
- Stochastic programming
- Petri-nets
- Fuzzy models

The available approaches will be discussed again focused on each characteristic, and the selected method will be shown in detail in Chapter 3.

2.2.3 Operational Scenarios of the Aircraft Turnaround Process

This thesis aims at the improvement of the aircraft turnaround process with current capacity by applying modeling and simulation technique for the development of an approach to provide a stable operational turnaround process. A review of the means for the enhancement of the aircraft turnaround process and that of the various methods for the modeling for the aircraft turnaround process are presented in sections 2.2.1 and 2.2.2.

Modeling of the aircraft turnaround process requires the operational scenarios which reflect a realistic environment in order to estimate reliable performance measures. In a realistic environment of airline management, most airlines define a “buffer time (padding)” into their flight schedules with a little extra time as a scheduling strategy to maintain their on-time record. The book ‘Airline Operations and Delay Management: Insights from Airline Economics’ [32] by Cheng-Lung Wu details the construction of the operational scenarios with the incorporation of buffer time.

It introduces several operational scenarios relevant to buffer time as illustrated in figure 2-4.

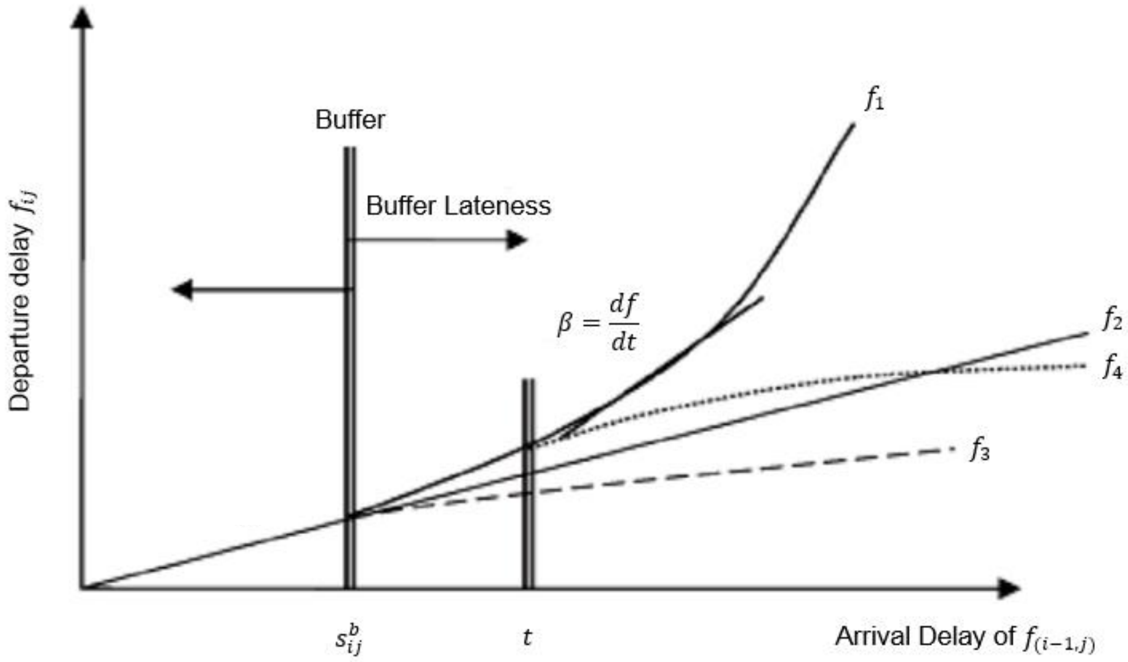


Figure 2-4 Relation between Arrival Delay and Departure Lateness [33]

If the flight arrival delayed less than or equal to the amount of buffer time, then the arrival delay will be absorbed. However, if the aircraft arrival delay is longer than the buffer, then there are several available scenarios to show the corresponding departure delay.

a. No-action (f_1): It shows the typical situation when the ground handling process is further disturbed by arrival delay through late luggage handling, and disruptions in ground handling schedules [33].

b. Linear proportion (f_2): The departure delays developed linearly proportional to arrival delays irrespective of the arrival delay time [33].

c. Take-action scenario 1 (f_3): Ground service providers may take actions to ensure punctuality. Thus, departure delay increase smoothly regardless of the increase of arrival delays [33].

d. Take-action scenario 2 (f_4): The airline terminal dispatchers may take actions to reduce the delay of departure [33].

The described operational scenarios motivate the next research question related to the measurement of impact between non-appointed arrival and turnaround process.

Research Question 1-2

How to measure the impact between non-appointed (late or early) arrival and turnaround?

In order to measure the impact between not-appointed arrival and turnaround, a new variable is introduced, named ‘schedule variability buffer.’ It has a role similar to buffer time. When sufficient schedule variability buffer is included, an unexpected arrival delay would be absorbed, and then the departure delay would be slight. The three cases would be defined:

- Ideal: Schedule variability buffer=0
- Robust: 0 < Schedule variability buffer < max
- Largest: Schedule variability buffer=max

In the ideal case the ground operation proceeds with no schedule variability buffer while in the largest case the ground operation proceeds with maximum schedule variability buffer to cover nearly 100% arrival delays. The robust case would have its value between that of the ideal and the largest case. Although, intuitively, it may seems that the largest case is the best amongst the available choices, owning to its ability to prevent all delays, the airlines would not be willing to schedule excessive schedule variability buffer due to scheduling costs incurred. Thus, finding sufficient schedule variability buffer is a crucial element for strategic and economic purposes. The usage of schedule variability buffer and its bounded condition into scheduling costs will be discussed in Chapter 7.

CHAPTER 3. APPROACH

This dissertation focuses on the improvement of the aircraft turnaround process with current capacity by developing a stable operational approach in comparison with the current working system. In order to get a thorough understanding of the current aircraft turnaround process, it is necessary to portray the process accurately. Thus, the general information of the aircraft turnaround process was reviewed in Chapter 2.

Chapter 2 proposes the concept of integrating the work procedures by including all the relevant stakeholders with the management of the relevant resources in a modeling and simulation environment so as to determine the optimal “schedule variability buffer”. In order to analyze the current aircraft turnaround process, previous research works have been reviewed within three groups: enhancement of the aircraft turnaround process, modeling of the aircraft turnaround process, and operational scenarios of the aircraft turnaround process.

In Section 2.2.1, regarding the enhancement of the aircraft turnaround process, the critical idea identified was the integration of work procedures including all stakeholders and management of relevant resources. In Section 2.2.2, the application of various modeling techniques about aircraft turnaround process was reviewed and discussed those pros and cons. In Section 2.2.3, the definition of padding (buffer time) was introduced, and operational scenarios with padding were identified from the literature review. Based on the role of padding, a new variable ‘schedule variability buffer’ was introduced to measure the impact of not-appointed arrival about the turnaround process.

The analysis of the current aircraft turnaround process in section 2.2 would be utilized to develop a stable operational approach. Before describing the proposed approach, the current work structure of the aircraft ground handling process with relevant stakeholders is introduced.

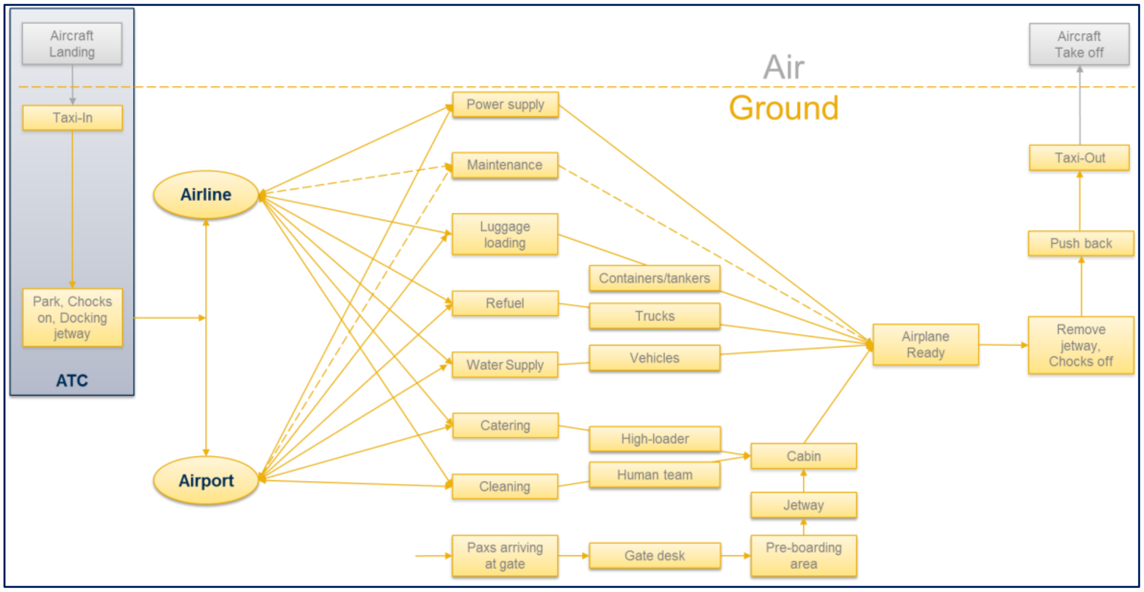


Figure 3-1 Current Turnaround Process with the Stakeholders [26][34]

Figure 3-1 shows the turnaround process with stakeholders under the current work structure. The state of the ground handling work structure can be divided as being in the scope of the direct or indirect management of airport authorities, airlines, or specialized ground handling companies. It is managed globally or partially by the airport's ground handling managers, airlines' ground handling managers, the specialized companies hired by the airport, or the specialized companies hired by airlines [35].

In the aircraft turnaround process, when an aircraft arrives, all ground handling work should be completed before its departure. This implies that the time needed to finish the process is crucial in determining if the flight will have an on-time departure, or not. As explained, the current aircraft handling process is operated by various agents under different management strategy. Delays in ground handling operations is caused by communication problems which arise among the large variety of stakeholders involving global actors (airports, airlines, air traffic control, air traffic management) as well as local actors (ground handlers, local suppliers, etc.), because those pursue different and sometimes contradictory goals that are difficult to achieve [36] . Thus, the secondary objective guiding the research work is formally stated as follows:

Sub-Research Objective

Implement a symbiotic turnaround process among different stakeholders

This leads to the formulation of the second research question dealing with the symbiotic turnaround process:

Research Question 2

How to make the symbiotic work flow with little investment?

A symbiotic flow has the advantage of being able to reduce the conflict among the stakeholders. Thus, the symbiotic work flow among stakeholders can contribute to a stable operational approach, which will then be associated with the improvement of the aircraft turnaround process with current capacity. The following section describes this in detail.

3.1 Proposed Approach

With the increasing demands in air traffic, there are considerable airport and airspace congestion along with flight delays. However, it is difficult to improve airport capacity and airspace with the goal of increasing the flight on-time performance. Therefore, it is necessary to define an innovative operational concept for airports in order to remove many operational constraints. It may include a transition over technologies, procedures or organizations, with retraining of personnel. There are ways to realize such a transition, for example, focusing on the interrelation among the components or aspects of each component.

The traditional approach to operating the turnaround process is executed by multiple service companies, using service vehicles for each type of activity [30]. To carry out the aircraft turnaround process, the companies should coordinate with each other and follow the constraints of tasks and resources for each aircraft [37]. Thus, the traditional work structure can be summarized as follows:

- No general standard or rule can apply to the aircraft turnaround process
- Various stakeholders collaborate, but they pursue their profit respectively

Section 2.2.1 has shown the state of the previous research where various attempts to improve the aircraft turnaround process and reduce delay time and cost were attempted. These attempts included the integration of the actions of all relevant stakeholders [15], the standardization and integration of the refueling process [16], and strategy of sharing ground resources [18]. However, the attempts were not focused on the whole process, but a fraction of the aircraft turnaround process.

Therefore, the proposed approach aims at the integration over the whole turnaround process within the current physical capacity. Success will result in an automated cost-efficient decision-making system inserted into the turnaround process to realize the integrated management of essential ground handling processes. The system will take a role in the communication among the ground handling agents, airline and airport personnel within the given operational frame.

The main task of the system is scheduling the robust work order by communicating with each work agent. In other words, it sequences the operations for aircraft following which it calls on each work agent to perform their service. It should share, at the right time, relevant data among simulation entities, then show the interaction at multiple levels. The proposed approach would be capable of handling non-appointed flight schedules identifying the necessary agents and their behavior.

Hypothesis 2

If the integrated management of the aircraft turnaround process is realized, then it will result in a decrease in the delay from the ground handling process and, hence, the direct operating cost.

3.1.1 Research Scope

The research work incorporates all activities from after the chocks-on the aircraft to before the chocks-off. Figure 3-2 shows the work scope marked by a rectangular box.

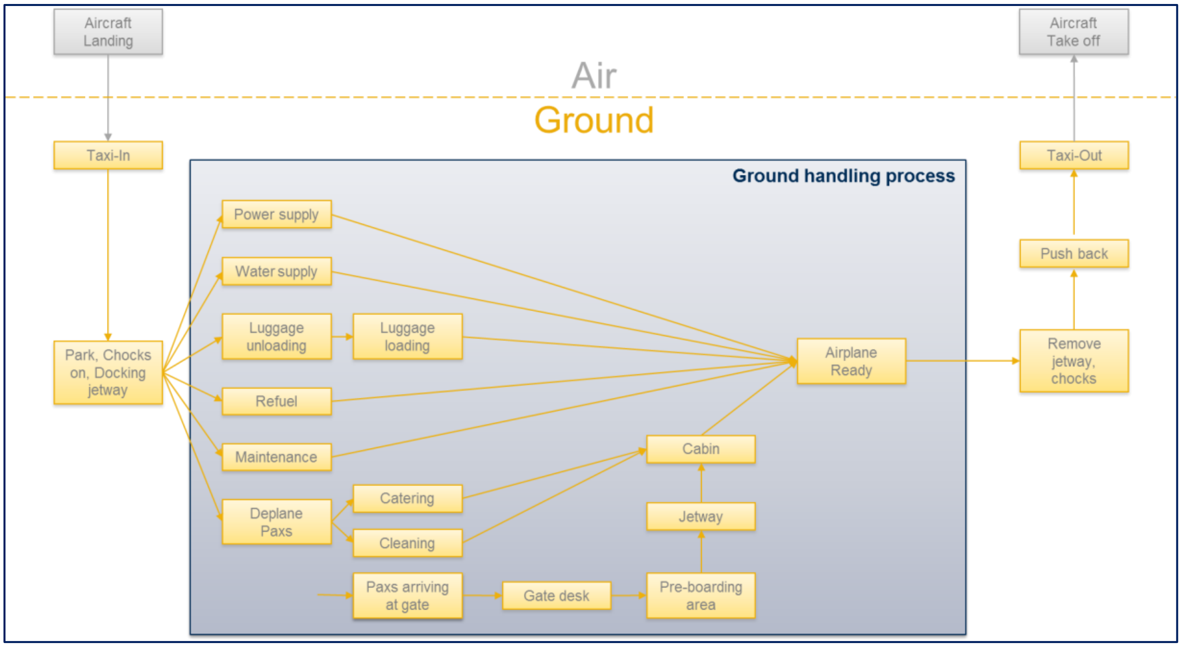


Figure 3-2 Definition of Research Scope

3.1.2 Application of Integrated Work Structure

As no general standard or rule can apply to the aircraft turnaround process [38], the current work can be expressed under the unintegrated structure by airline or airport's authorities. In such a scenario, the specialized ground handling company does not have authority for operations, because they report to the airlines or airport.

3.1.2.1 <u>Authority of the airline</u>

The first concept is that of operation under the airline's authority, i.e., the airline is the only entity which has the role of communicating with the decision-making system. Figure 3-3 shows the concept of the airline's authorities.

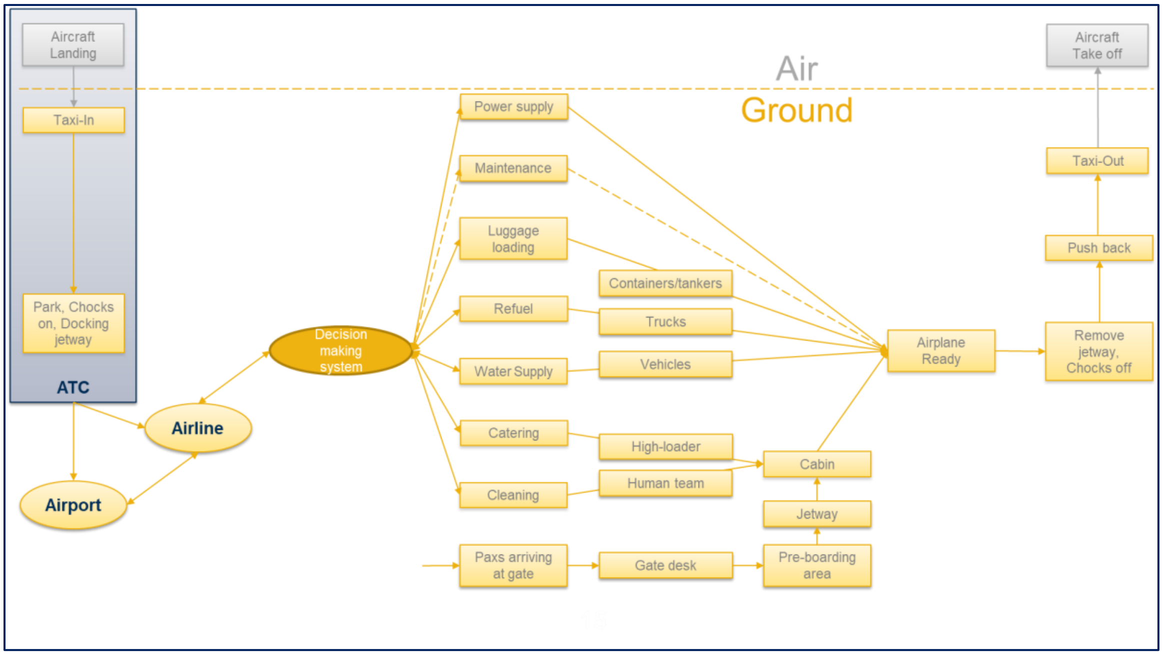


Figure 3-3 Authority of the Airline

Although such an approach would enable the optimization of an airline's on-time departure, there would be conflicts that arise in cases where multiple airlines are considered. While constraints expressing these conflicts may be established, it is unable to identify these constraints a priori. Another factor making such an approach untenable is the airports inability to control the ground system.

3.1.2.2 Authority of the airport

The concept of airline's authority has difficulties to control the whole ground system and to guarantee each airline's profit. Thus, an alternative formulation of the operation under the airport's authorities is considered. Here, the airport is the only entity that dictates the communication with the decision-making system. Figure 3-4 shows the concept of the airport's authorities.

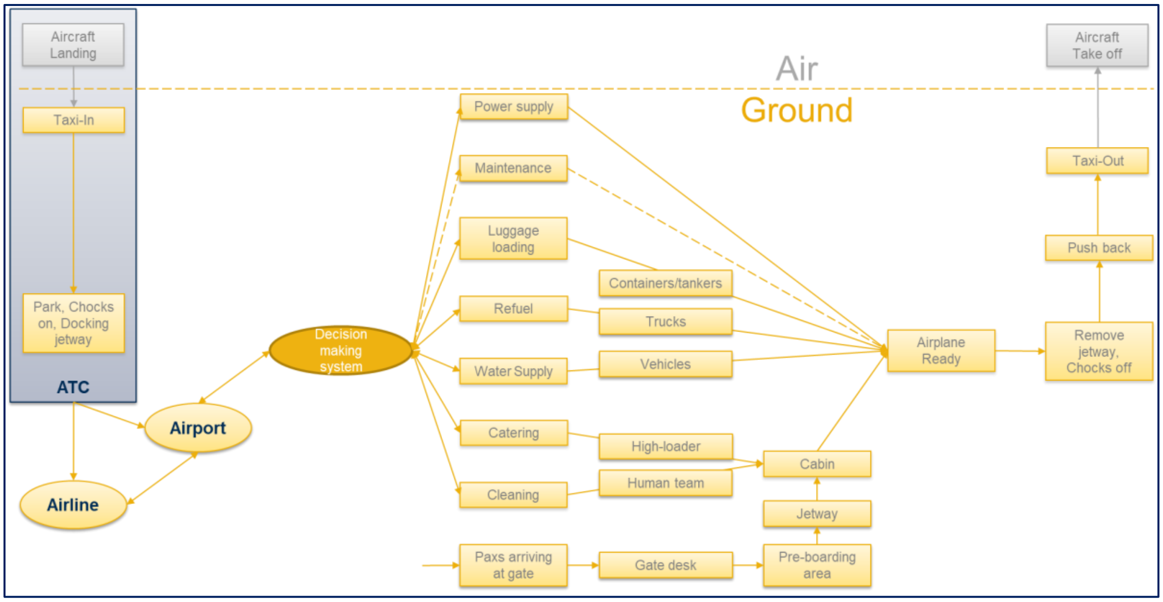


Figure 3-4 Authority of the Airport

While this concept has the advantage of controlling overall ground space, i.e., the ground management should be aimed at reducing the number of delayed flights and total delay time, it cannot guarantee that all airlines would be operated in a manner to minimize their delay times.

3.1.2.3 The hybrid concept of authority

Section 3.1.2.1 and 3.1.2.2 implies that the relevant stakeholders of the aircraft turnaround process pursue different and sometimes contradictory objectives that are difficult to achieve [36]. Thus, it is necessary to propose a compromise concept. Figure 3-5 shows the hybrid concept of authority.

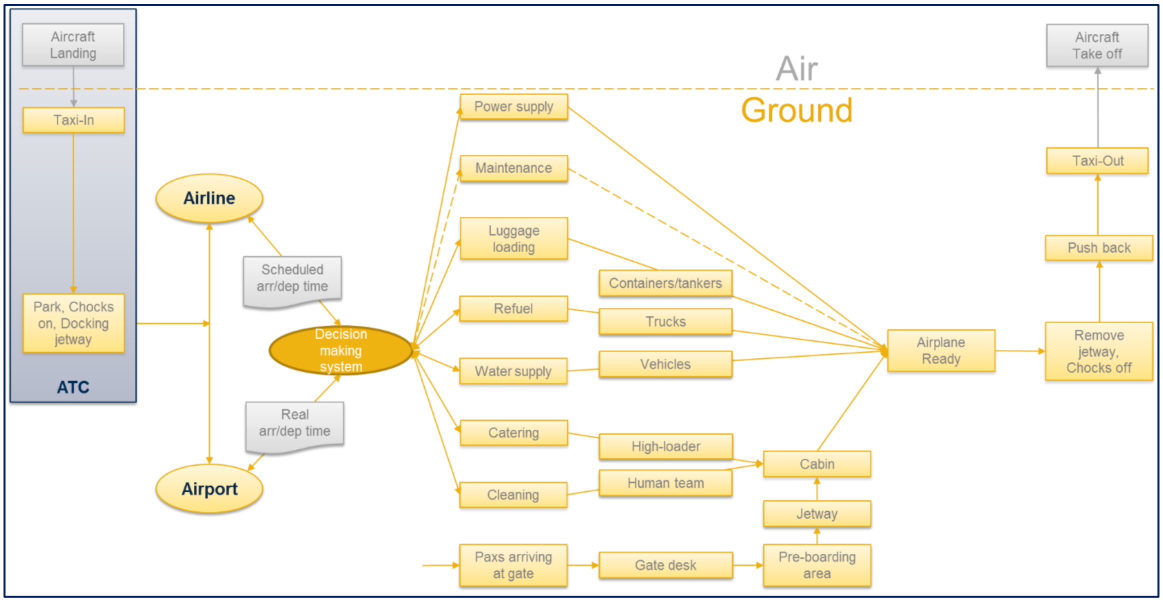


Figure 3-5 Hybrid Concept of the Authority

The hybrid concept permits stakeholders can communicate and share relevant data with the decision-making system under a centralized work structure. It is a symbiotic approach for airlines and airport to input all scheduled departure times and overall information on the ground area. Given that the concepts of airport and airline authority are complementary in nature, it is hypothesized that the hybrid concept would exploit the benefits of both the approaches.

3.2 Modeling and Simulation

While section 3.1 introduces an approach integrating the entire turnaround process in a simulation framework, whose success would result in an automated cost-efficient decision-making system, it is essential to address the methodology that needs to be employed to develop the integrated system. This is indicated by the third research question, given as:

Research Question 3

What is the approach to develop an integrated system?

In Chapter 2, the various methods of previous research work have been discussed, and the advantages of modeling and simulation techniques have been described. Many researchers have adopted common types of closed-form analytical mathematical models to examine air traffic delay and congestion because such models are capable of providing several solutions simultaneously [39].

However, mathematical modeling may not be useful for large and complex problems [39]. Thus, for those problems, researchers have often relied on modeling and simulation techniques as a replacement. Since simulation allows researchers to experiment with different resource and operating policy alternatives without disturbing the actual system, there are a wide variety of applications of simulations in the air transport system [39]. Furthermore, simulation is the proper environment to test ‘what if?’ scenarios. It allows the users to test and better understand the system and alternative ways [84].

In terms of simulation techniques, a more useful tool for large and complex problems is a Discrete Event Simulation (DES) [40]. DES is a simulation methodology that shows the behavior and performance of real-life process or system [84]. It consists of a series of events that take place over time, which represents an instantaneous occurrence that changes the state of system [85].

DES allows us to do large scale simulations with computational efficiency [41], and includes the stochastic components and simulates a dynamic system based on a chronological sequence of events. Thus, DES is commonly used for the system analysis if the system consists of discrete and asynchronous events [42][43]. For the systems featured by complex processes with infrastructure at a limited capacity, DES is often selected [44]. The airports are, therefore, ideally suitable for the application of such simulations because of the stochastic and dynamic characteristics [45].

From the practical perspective, a suitable model to simulate the turnaround process would be on that is able to model the operational uncertainties and investigate the operational activities with the required level of detail [46]. Therefore, the basic premise is that the use of DES to evaluate the proposed approach for airport operations.

Hypothesis 3

DES (Discrete Event Simulation) can realize the integration of the aircraft turnaround process.

DES process is based on entities, state variables, events, and the Future Event List (FEL). Each event generates at an instant of time and records a change of state in the system, thus ensuring efficient performance [68]. It starts with the first event in the FEL, and then the other scheduled events are added as the simulation progresses.

3.2.1 Life Cycle

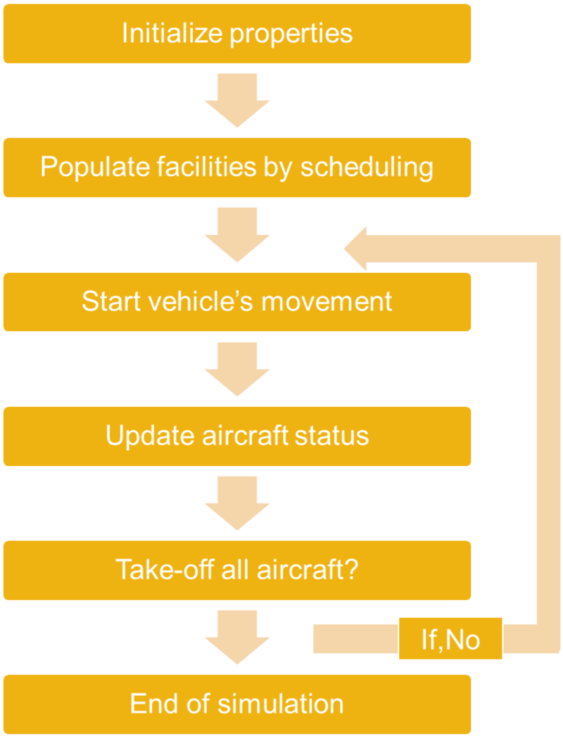


Figure 3-6 Whole Framework of Simulation

The life cycle of simulation represents the main execution loop. It initializes all inputs including the number of aircraft, type of aircraft, flight plan, the scheduled time for departure and arrival, the scheduled time for turnaround activity, the number of ground resources/staffs. The detailed input is as illustrated in Chapter 4. Then, the facilities are staffed at the initial position, and the movement starts. After the movement of all ground facilities, the status of aircraft can be updated. The simulation terminates once each flight scheduled for departure is processed.

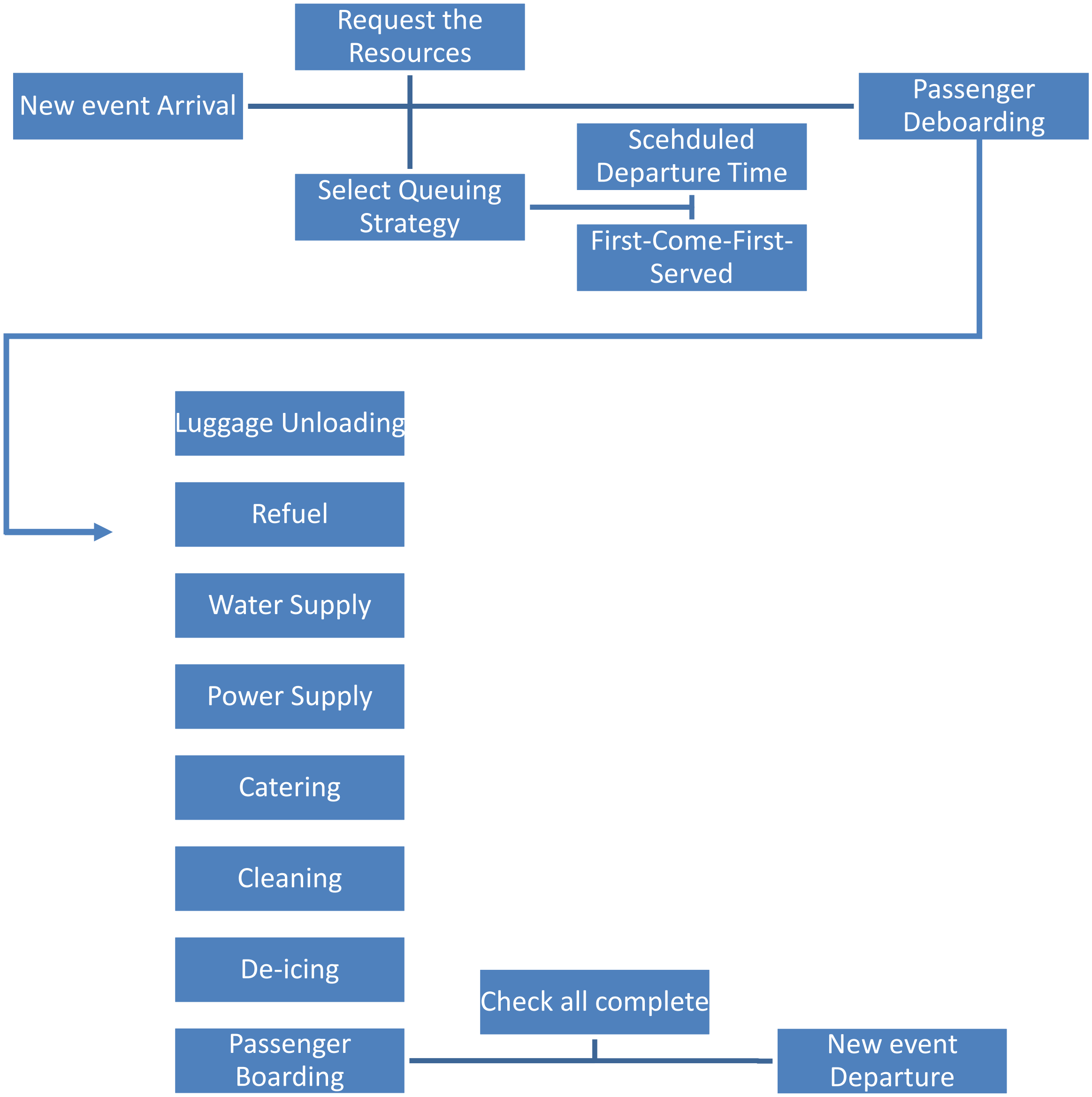


Figure 3-7 Aircraft Turnaround Process in Simulation

The whole process of turnaround to be realized in the simulation is shown in figure 3-7. The aircraft is “generated” by an arrival schedule. The aircraft, defined by a model, then processes its model-specific ground activities requesting services. The system queues the aircrafts based on an assessment of its priority causing the aircraft to wait for the resource availability which in turn triggers the processing of individual activities.

To explain the detailed process, refueling is picked as an example. It models the hub and the aircraft that arrive at the station for refueling. There is a limited number of resources (trucks) for refueling service. Thus, the resources should be modeled as a ‘Priority Resource.’ The aircraft assigned at a gate requests the refueling, then the resources move from the station along with their other requests. Once a decision-maker assigns the aircraft a refueling resource, they take the required amount of fuel from the fuel pump. Having completed the service for the aircraft, the resources move to the next aircraft. The other services are analogous to the example. When all services are completed, the aircraft is ready for take-off, releasing the assigned gate for the next arrival.

3.2.1.1 Modeling component

The simulation models the different ground handling activities involved in the turnaround process such as, Passenger deboarding, Luggage unloading, Supplying Power, Aircraft Maintenance, Luggage loading, Refueling, Supplying water, Waste water, Catering, Cleaning, and Passenger boarding.

These entities will be linked by the model configuration of the aircraft that is incorporated into the system. The system schedules the arrival and docking of aircraft as per a defined schedule. The system further handles resource/service requests from the aircrafts. These requests will be handled by passing messages to the requested service that will create an event in that service's future event list.

The internal processes of each service should add the necessary events; for example, the refueling truck should be reloaded if the fuel in the tank is diminishing. The services simulate the transportation of its resources from one gate to another.

3.2.1.2 Rules

There will be a hub for work facilities, which support supplying power, maintenance, luggage loading, refueling, supplying water, catering, and cleaning. Additionally, maintenance is only required if there is a malfunction with the aircraft from the check-up test.

For safety purposes, the critical path for most cases should follow the local causality constraints. The details of the critical path will be discussed again in chapter 4. Examples of constraints can be of the type, passenger boarding cannot coincide with cleaning. Also, the total ground time required for each aircraft is up to the fulfillment of the sequential execution of events under local causality constraints across all logical processes.

3.2.2 Cost Modeling

The performance of each aircraft in the simulation is evaluated using indicators such as delay and waiting time for calculation of DOC. This enables the investigation of the capability for a more efficient ground operation logistics by the stability of the turnaround process while taking into account the cost incurred.

The DOC+I (Direct Operating Cost plus Interest) model [47][48] illustrates the aircraft-related costs in full and has the important advantage of reflecting airline costs in a US deregulated environment, thus the operator uses that model often [49]. The model includes flight and cabin crew cost, airframe and engine maintenance cost, landing fee, navigation fee, depreciation, insurance and interest by using aircraft specs i.e., maximum takeoff weight and thrust [50]. The cost terms are expressed by the following units: $/hour,

$/mile, ¢/seat-mile, or for cargo aircraft regarding ¢/ton-mile [51]. The cost terms regarding $/mile represent the maximum loss with a partially filled aircraft, and the cost terms regarding ¢/seat-mile, or ¢/ton-mile represent a fare that should be charged with reasonable load factors [51].

By definition, the DOC+I model calculates the DOC of an aircraft from the costs incurred due to different cost terms over a year [52]. The DOC+I can be mathematically represented as:

Table 3-1 DOC+I Model [47][48]

$C_{DOC} = C_{DEP} + C_{INT} + C_{INS} + C_F + C_M + C_C + C_{FEE}$	
$C_M = C_{M,AF} + C_{M,PP}$	
$C_C = C_{C,CO} + C_{C,CA}$	
$C_{FEE} = C_{FEE,LD} + C_{FEE,NAV} + C_{FEE,GND}$	
C_{DEP}	Depreciation cost.
C_{INT}	Interest cost.
C_{INS}	Insurance cost.
C_F	Fuel cost.
C_M	Maintenance cost: airframe maintenance ($C_{M,AF}$) and the power plant maintenance($C_{M,PP}$)

C_C	Crew cost: cabin crew ($C_{C,CO}$), and the cockpit crew ($C_{C,CA}$)
C_{FEE}	Fees: landing fees ($C_{FEE,LD}$), navigation charges $\left(C_{FEE,NAV}\right)$ and ground handling charges ($C_{FEE,GND}$)

However, the DOC+I model is not an appropriate way to examine the cost trade-off between the schedule variability buffer and the operation disrupting delays, because there are many terms that are unrelated to the aircraft turnaround process. Additionally, the DOC+I model does not consider the variables related to the ground handling process: Cost for ground handling staff and Passenger-related cost [47][48].

Thus, the current research work would proposes the utilization of a modified DOC+I method with these categories included. Table 3-2 shows the suggested DOC+I Method including the missing variables.

Table 3-2 Suggested DOC+I Model for the Aircraft Turnaround Process

$C_{DOC,TA} = C_C + C_{FEE} + C_P$	
$C_C = C_{C,CO} + C_{C,CA} + C_{C,GS}$	
$C_{FEE} = C_{FEE,\mathrm{AP}} + C_{FEE,GND}$	
C_C	Crew cost: the cabin crew ($C_{C,CO}$), the cockpit crew ($C_{C,CA}$), and the ground staff ($C_{C,GS}$)

C_{FEE}	Fees. The sum of airport charges ($C_{FEE,\mathrm{AP}}$) and ground handling charges ($C_{FEE,GND}$)
C_P	Passenger-related cost. The compensation of flight delay.

The overall DOC is calculated as the sum of all the cost terms in the aircraft turnaround process via Vensim. Vensim provides a detailed model structure by including variables represented by lines of text describing each of them and links among variables [87]. Mathematical equations or functions can be defined to utilize or create variables in Vensim. The development of DOC+I model for the turnaround process will be discussed in chapter 7 in detail.

3.3 Performance Evaluation

3.3.1 Queuing Criteria

Modeling and simulation techniques with DES is applied to evaluate the proposed concepts for the aircraft turnaround process. If there were only one flight landing at the airport, it would not pose any difficulty to the turnaround process. However, there are many aircraft landing at the hub airport, even if the airport is small. It means the decision-making system should designate who has priority in order to complete the ground handling process. This motivates the research question:

Research Question 3-1

What is the primary criterion to create a queuing model of arrived aircraft?

The prioritization of aircrafts necessitates standardization in the process of identifying the entity, in the process of ground handling, with the most need of resources. An example of this standardization would be the scheduled departure time of the aircraft as a means for the identification of the prioritized aircraft.

Hypothesis 3-1

If the scheduled departure time is assigned as a higher priority, then it will result in a more stable solution for turnaround time.

The queuing model from the scheduled departure time is utilized to study the propagation of delay through the arrival of aircraft and ground handling service. Such a model is evaluated under several operational scenarios including unexpected events and constraints.

3.3.2 Turnaround Time Allocation (TTA) Model

Section 2.2.3 discusses three distinct cases for the classification of the 'schedule variability buffer'. One of the cases has a bounded condition, called it 'robust case'.

- Ideal

$$\text{Schedule variability buffer} = 0$$

- Robust

$$0 < \text{Schedule variability buffer} < \text{max}$$

- Largest

$$\text{Schedule variability buffer} = \text{max}$$

The value of a robust case would identify the solution having the optimized cost. The robust case can be interpreted as the trade-off between delay costs and scheduling costs where the higher turnaround schedule variability buffer reduces the associated delay cost both for passengers and the airline, but increases the opportunity cost of using aircraft time in other revenue-making flight operations.

A cost minimization model, called the Turnaround Time Allocation (TTA) model, is developed as a tool to optimize the allocation of the schedule variability buffer in the context of the trade-off situation [32].

Table 3-3 is cost minimization model to optimize the schedule variability buffer. It will be applied to find the value of the robust case and derive the total cost.

Table 3-3 Cost Minimization Model to Optimize the Schedule Variability Buffer

$C_T = \alpha D_C + (1-\alpha) S_C, \ \ 0 \le \alpha \le 1$			
C_T: Total cost	D_C: The expected cost of delay	S_C: The cost of scheduling	α: Weight factor
$D_C = \int_0^\infty [C_P(d_{ij}^D) + C_{AC}(d_{ij}^D)] g_i^{\prime}(d_{ij}^D) d(d_{ij}^D)$			
$C_P(d_{ij}^D) = \int_{d_{ij}^D} \gamma_P^m(d_{ij}^D) d(d_{ij}^D)$, Passenger delay cost as a function of a departure delay time			

$\gamma_P^m\left(d_{ij}^D\right)$: Chosen marginal delay cost function of passengers

$C_{AC}\left(d_{ij}^D\right) = \int_{d_{ij}^D} \varphi_{AC}^m\left(d_{ij}^D\right) d\left(d_{ij}^D\right)$, Aircraft delay cost as a function of departure delay time

$\varphi_{AC}^m\left(d_{ij}^D\right)$: Chosen marginal delay cost function of aircraft

$$S_C = C_{AL}\left(s_{ij}^b\right) = \int\limits_S \delta_{AL}^m\left(s_{ij}^b\right) d_G\left(s_{ij}^b\right)$$

$C_{AL}\left(s_{ij}^b\right)$: Opportunity cost in airline scheduling

$\delta_{AL}^m\left(s_{ij}^b\right)$: Marginal schedule time cost function which reflects the opportunity cost of flying flight f_{ij} by aircraft type

CHAPTER 4. INPUT MODELING

The primary approach of the dissertation is the integration over the whole procedure of the turnaround process within the current physical capacity in order to implement the stable operational concept.

In order to portray the traditional turnaround system accurately, the general information of the aircraft turnaround process was reviewed in Chapter 2 by analyzing the various literature and research works. It highlights the traditional system’s weakness:

- No general standard or rule for the aircraft turnaround process
- The collaboration of various stakeholders by pursuing each profit respectively

The proposed approach resulted from the improvement of the weakness was discussed in Chapter 3. In section 3.1, the proposed approach was discussed in detail with the work scope and explained the expected achievements. Since the approach aims at the integration of the whole process, it also discussed a centralized work structure by the authority of different stakeholders.

In section 3.2, the method for the development was discussed based on the review of the literature and the characteristics of the problem. The selected method ‘Discrete Event Simulation’ was introduced with the simulation modeling structure and life cycle. Since the output of the simulation would be a part of the cost calculation, the cost modeling was also introduced here.

In order to proceed with the proposed approach, it is necessary to build the simulation with reasonable inputs. Thus, this chapter will introduce how to define the required inputs for the implementation of the approach.

There are multiple stages in here. In the first stage, there is an analysis of flight arrival data. Figure 4-1 provides the process of data analysis and indicates what section shows the details of each stage. It starts with the collection of flight data that satisfying the constraints: origin/ destination, and period. Then, data analysis will proceed to capture the features. To characterize the level of congestion, the tracked variables are a histogram of delayed flights, the delay ratio, and the delay time distribution.

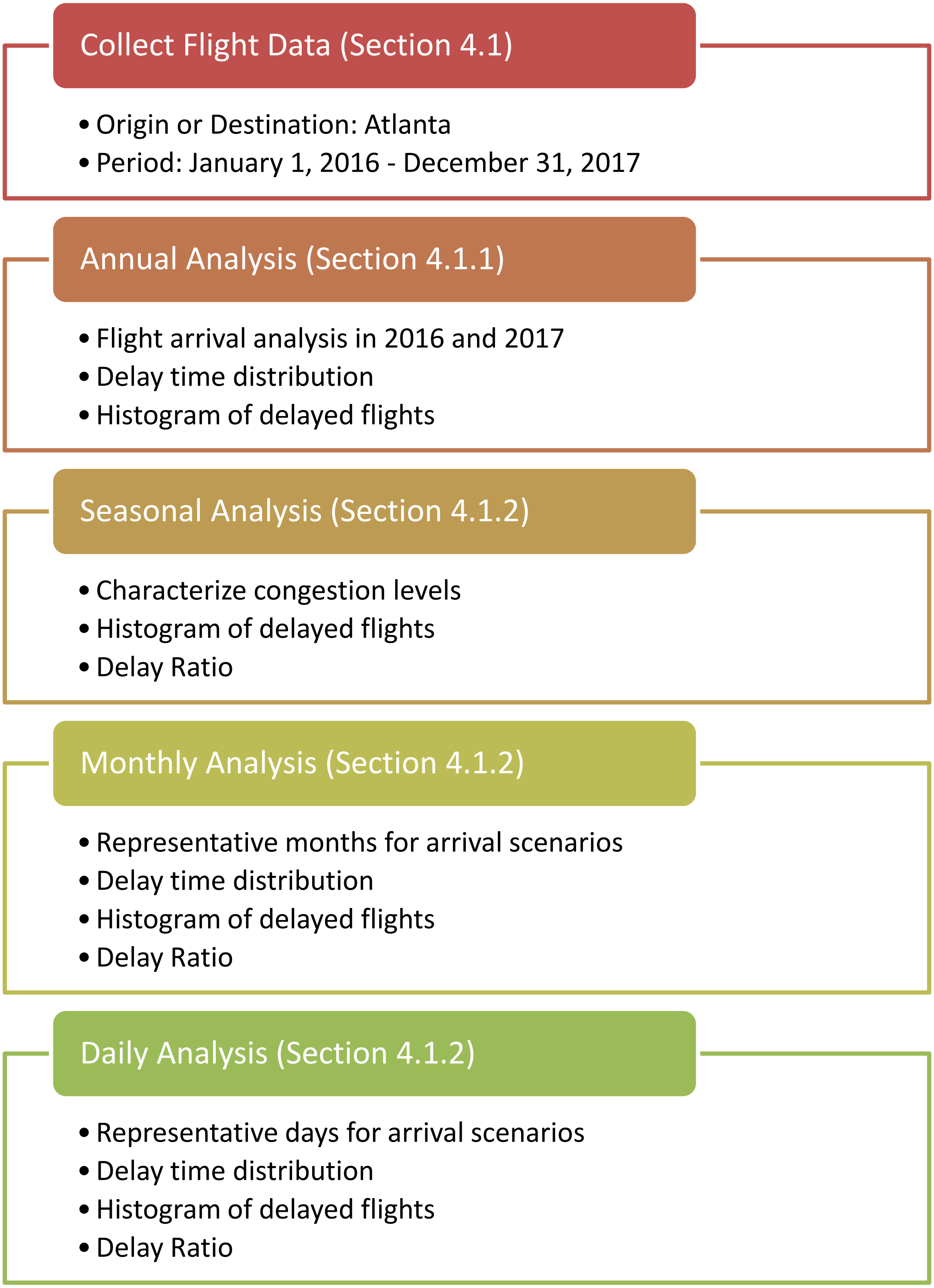


Figure 4-1 Data Analysis Process for Flight Arrival Scenarios

The second stage shows the candidates for the operational scenarios by the level of congestion based on the first stage. Figure 4-2 illustrates the objective of each analysis. To select the flight arrival scenarios, each analysis is required.

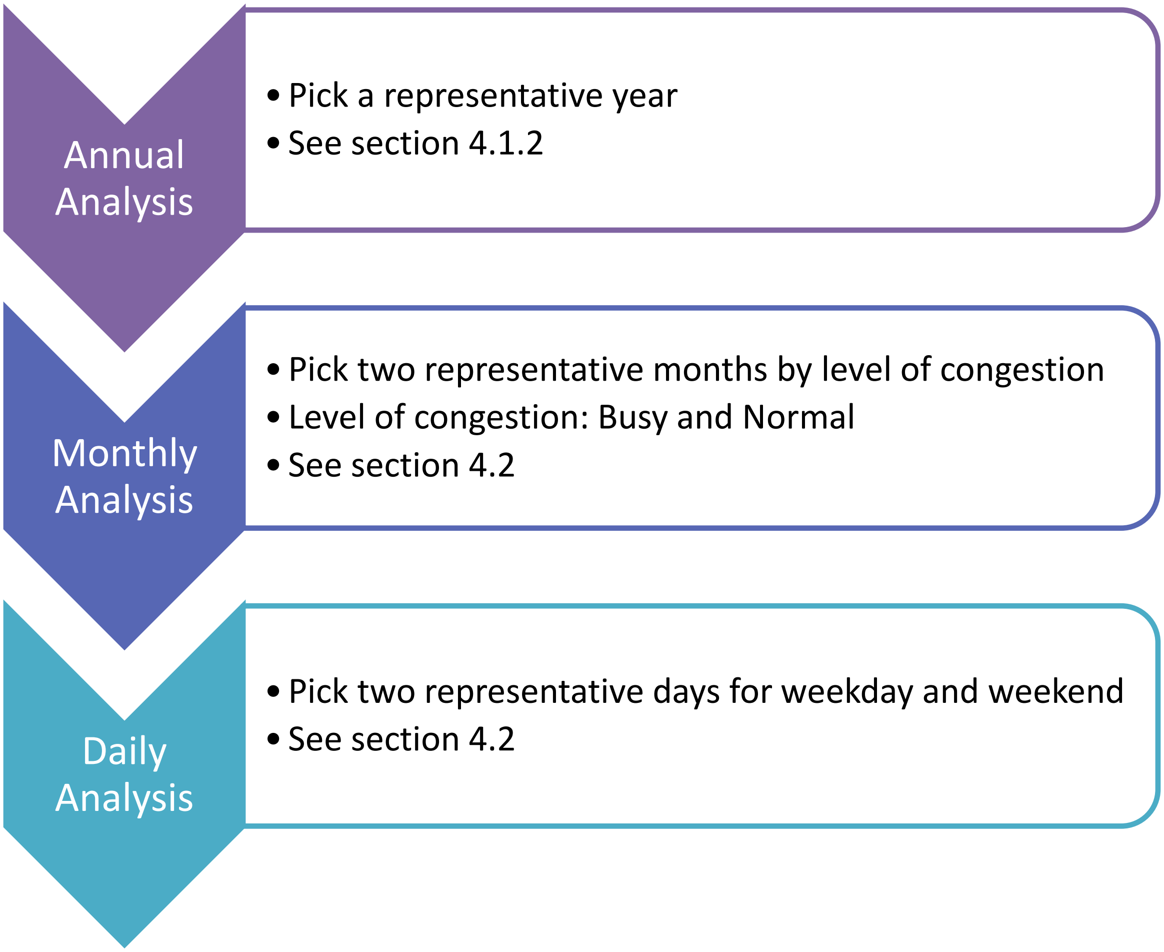


Figure 4-2 Objective on the Stage of Analysis

The last stage discusses the aircraft turnaround process and its time by aircraft model. It refers to the aircraft manual by the manufacturers. Figure 4-3 represents the data analysis process for the aircraft turnaround. Due to the insufficiency of the information, the number of resources will be handled with three cases of scenarios.

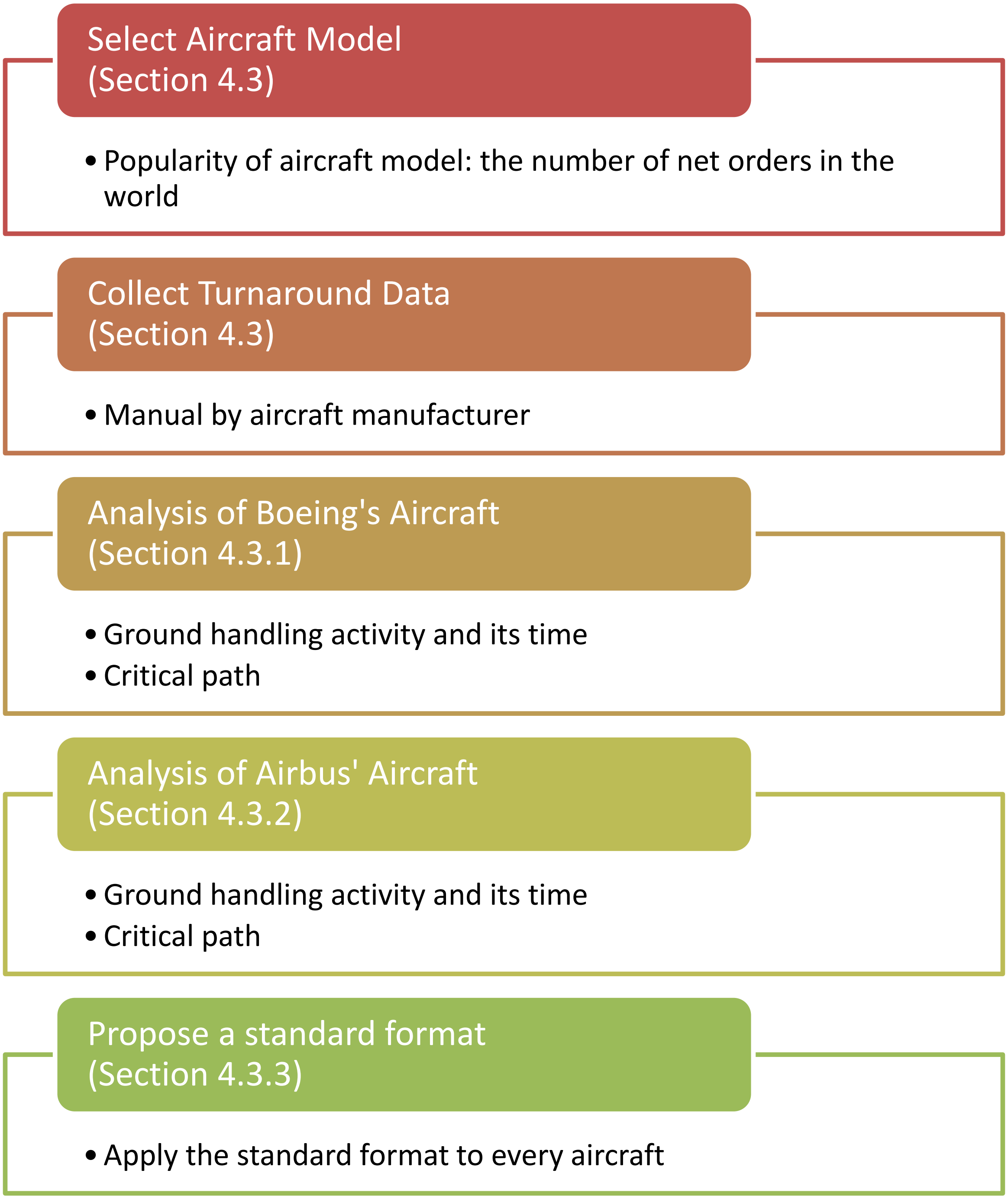


Figure 4-3 Data Analysis Process for Aircraft Turnaround

4.1 Flight Data Analysis

In chapter 5, the simulation modeling process will do the experiments with an airport as a case study. Thus, it requires selecting one airport in the United States. The airport will be applied to estimate the physical dimensions upon which to base the time for resources to travel because it represents a simulation environment. Since the Atlanta Hartsfield-Jackson Airport has been ranked #1 in passenger traffic and scheduled flights, it is selected.

In order to apply the airport into the simulation process, the prerequisite step is the analysis of flight data. Section 4.1 will focus on that analysis with the historical flight arrival data from BTS (Bureau of Transportation Statistics) and show how to use it.

4.1.1 Annual Data Analysis

Historical data can be accessed through the BTS website (https://www.bts.gov). The collected data satisfied with the following condition:

- Destination: Atlanta
- Date: 2016 Jan 1 to 2017 Dec 31

At first, the distribution of non-appointed arrival is analyzed. A flight is considered non-appointed arrival when it did not arrive on the scheduled arrival time. Thus, non-appointed entries included early and late arrivals. Since the early arrivals may impact the turnaround scheduling, they should be considered. The following figures show the time difference distribution based on the scheduled arrival time. Figure 4-4 shows the year 2016's result, and Figure 4-5 shows the year 2017's result.

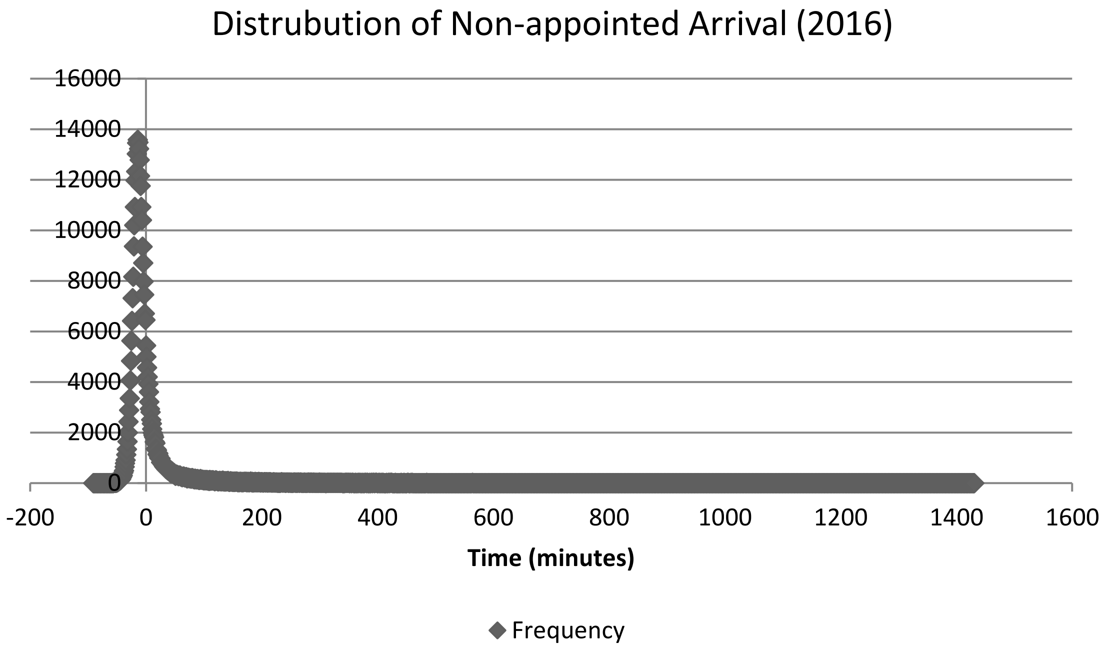


Figure 4-4 Distribution of Non-appointed Arrival in 2016

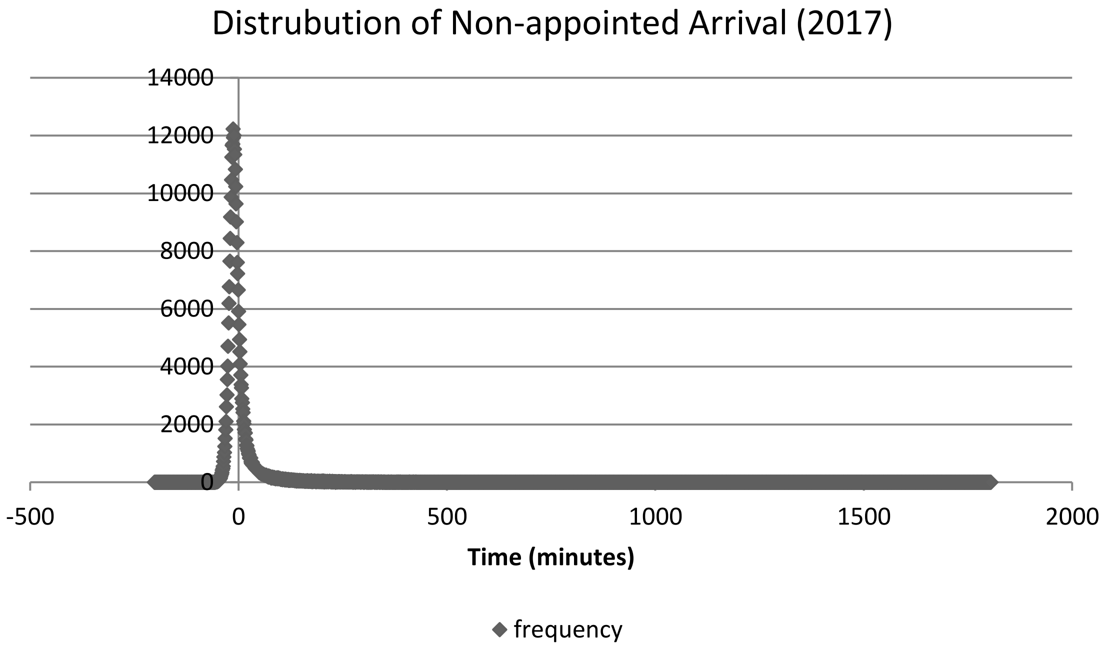


Figure 4-5 Distribution of Non-appointed Arrival in 2017

It is explicit that both annual data have differences. The year 2017 has a broader time range and smaller appointed entries than 2016. Thus, the flight data in 2017 will be utilized because it is worse and a more recent scenario. The mixture of 2016 and 2017 data was one of the available options. However, it is not the right approach because it just spreads the delay in an unrepresentative way. Therefore, the year 2017's flight arrival will be introduced in detail in the next section.

4.1.2 Flight Arrival in 2017

In section 4.1.1, the flight data in 2017 has been selected to apply into the simulation modeling process because it has worse arrival scenarios. There are many variables from meteorological factors to airside restrictions which affect the ground activity [11]. Some of the variables are more predictable than the others, such as the status of crew and resource. However, there are also some other variables that cannot be predicted such as sudden maintenance failure or climate change.

In general, high traffic affects the aircraft turnaround process, and it results in delays. Thus, at first, seasonality will be reviewed because it is prevalent to have more delays in the summer and winter season. Summer season has higher demands than the other seasons, and winter season has more delays due to the weather and loading delays. [11]. Then, it will be analyzed with the month, and the day of the week to define the operational scenarios by the level of congestion: busy, and normal.

4.1.2.1 Season and Month

Volatile between seasons, large traffic demands influence the ground activity [11]. Demands should be a reason of delay if there is no growth in handling resources. Figure 4-6 shows the seasonal impact in the Atlanta airport. In the summer season, there were more delays than the others as expected. That means, to define the operational scenario, the seasonal effect is a crucial factor.

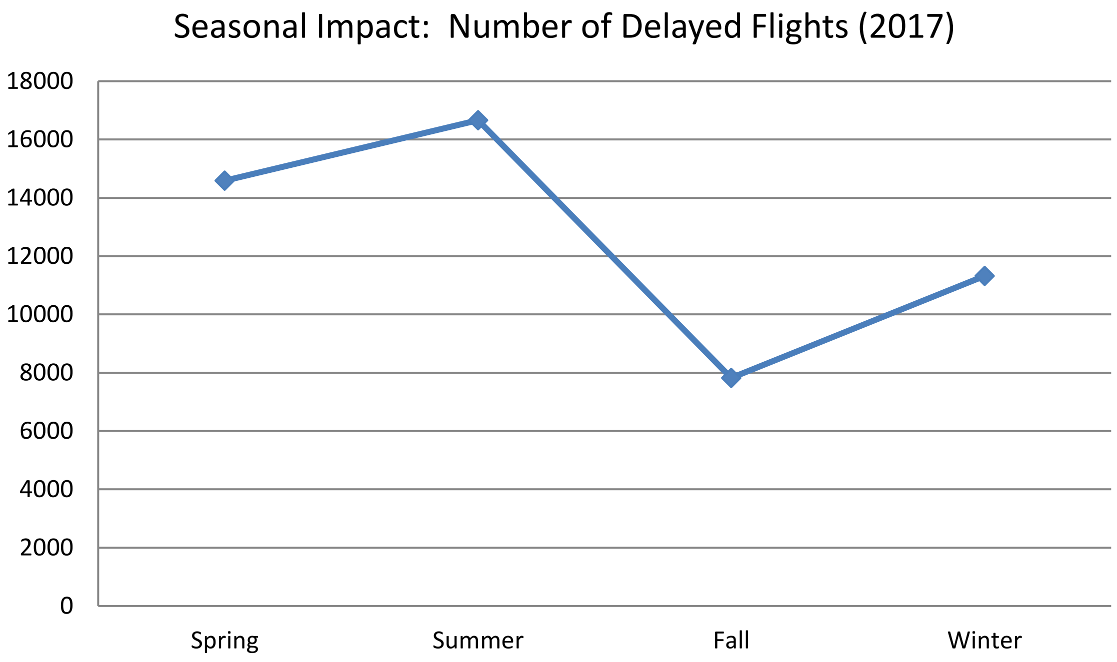


Figure 4-6 Seasonal Delay in 2017

Table 4-1 shows the summary of seasonal impact with a period, the number of delayed flights and the percentages.

Table 4-1 Seasonal Delay in 2017

Season	Period	Number of Delayed Flights	Percentages of Delay (%)
Spring	Mar 1 – May 31	14587	28.95%
Summer	Jun 1– Aug 31	16661	33.06%
Fall	Sep 1– Nov 30	7823	15.52%
Winter	Dec 1– Mar 31	11321	22.47%
		Total 50392	Total 100%

Every season takes three months, for example, the summer taking from June 1st to August 31st. In order to see the difference between the months in the same season, the monthly delay should be analyzed.

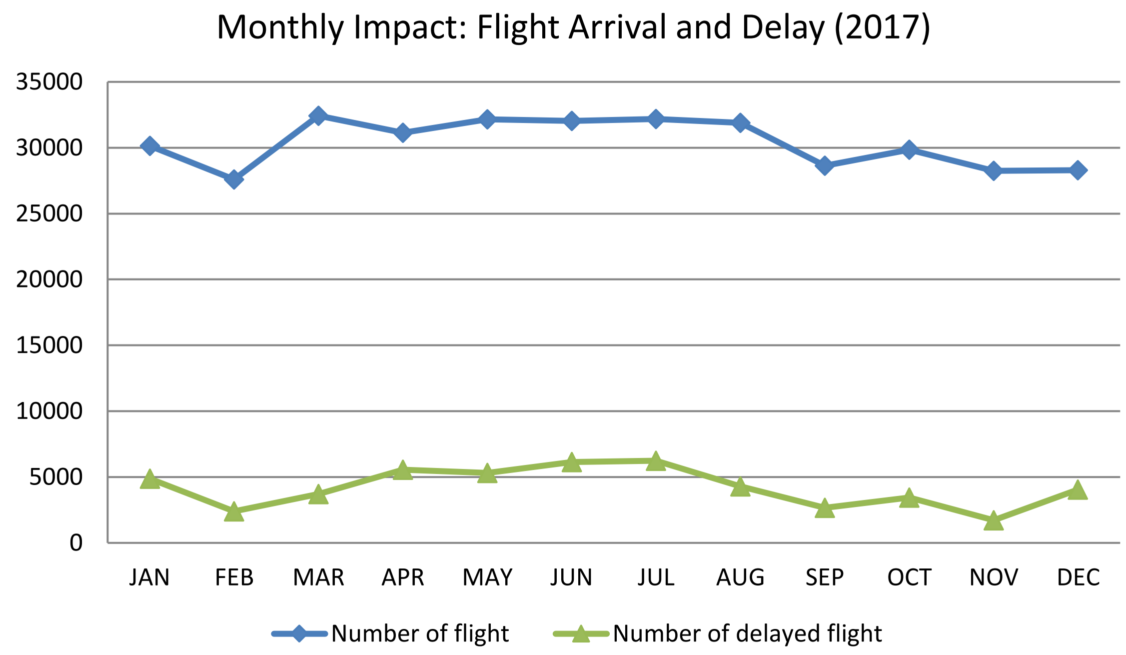


Figure 4-7 Monthly Number of Arrived Flight and Delayed Flight in 2017

Figure 4-7 shows the monthly record of total flight arrival and how many delayed flights. In general except for March, if there is a large number of arrived flight, then there is also a large number of delayed flights. Based on figure 4-7, the possible candidates of the busy scenario are April, June, and July. For the normal scenario, the possible candidates are February and November. It is meaningful to see how many flights are on-time or delayed, but the delay time is also a significant measure because the short time delay impact and long time delay impact is entirely different.

Thus, figure 4-8 represents the monthly delay time in 2017. Based on the statistical data, there was an amazingly longer delay time in April. However, it does not mean April should be the representative for the busy scenario because of the possibility of an unexpected incident which resulted in a longer delay.

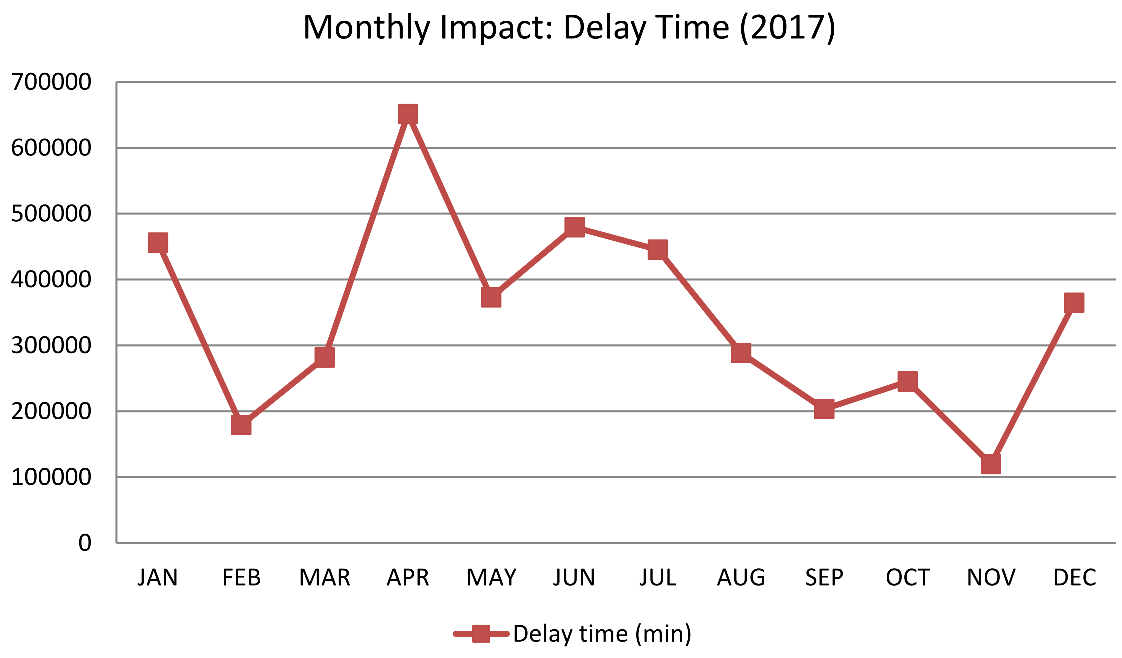


Figure 4-8 Monthly Total Delay Time in 2017

To find the candidate for operational scenarios by the level of congestion (Busy, Normal), the next measure being analyzed is the ratio. Figure 4-9 shows the ratios. There are two ratios would be calculated by the followings:

$$x = number\ of\ flight$$

$$y = number\ of\ delayed\ flight$$

$$ratio1 = \frac{y}{x}$$

$$ratio2 = \frac{y}{\sum y}$$

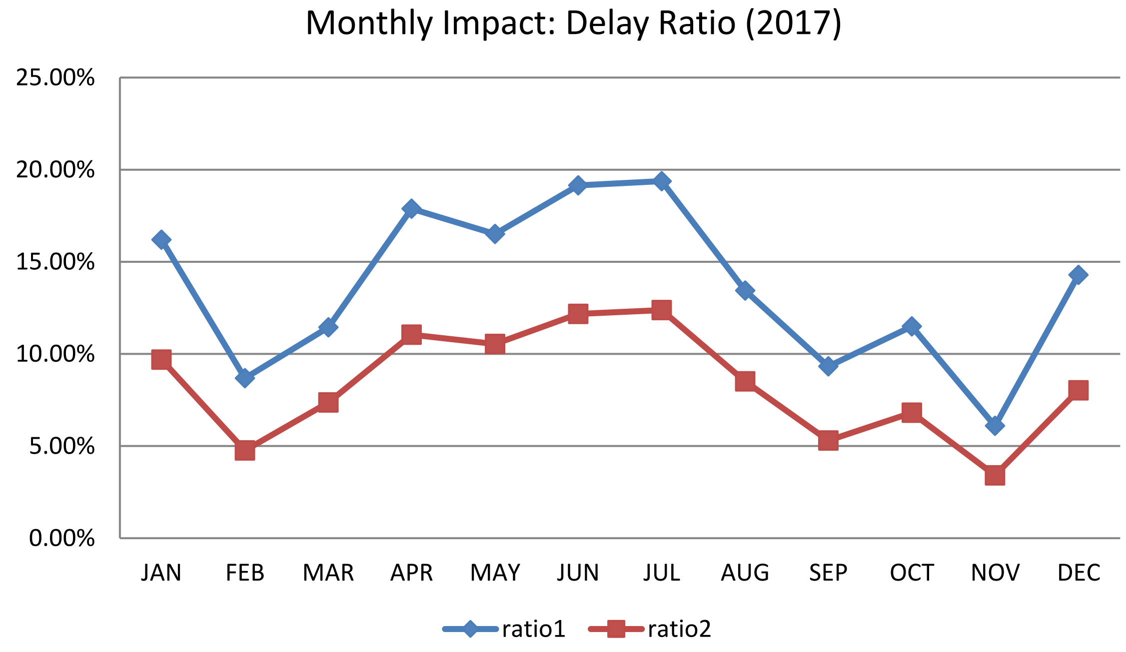


Figure 4-9 Monthly Delay Ratio in 2017

Table 4-2 shows the summary of monthly impact with the number of flights, the number of delayed flights, delay time and the ratios. Since July has the highest for both ratios and the number of delayed flights, it is selected for the busy scenario. Also, November is selected for the normal scenario because of lowest ratios and number of delayed flights.

Table 4-2 Monthly Delay in 2017

Month	Number of Flights ···(a)	Number of Delayed Flights··· (b)	Delay Time (min)	Ratio of Delay (b) / (a)	Ratio of Delay (b) / ∑(b)
January	30135	4880	456100	16.19%	9.68%
February	27594	2398	178950	8.69%	4.76%
March	32430	3712	281688	11.45%	7.37%
April	31131	5566	651324	17.88%	11.05%
May	32151	5309	372759	16.51%	10.54%
June	32037	6135	479431	19.15%	12.17%
July	32189	6238	445272	19.38%	12.38%
August	31901	4288	288114	13.44%	8.51%
September	28643	2673	203115	9.33%	5.30%
October	29844	3430	244835	11.49%	6.81%
November	28248	1720	119524	6.09%	3.41%
December	28293	4043	364504	14.29%	8.02%
Total	364596	50392	4085616		100%

4.1.2.2 Day

A representative day with significant delays is selected to investigate the resilience of the turnaround process under challenging conditions relevant to this study. The day should consider the feature of the weekends (Friday, Saturday, and Sunday) and weekdays (Monday, Tuesday, Wednesday, and Thursday) because people usually have more travel at the weekends. Thus, two representative days will be selected as follows: one from the weekdays and another one from the weekends. To select the best candidates, each day of the week will be analyzed and show the difference between the days.

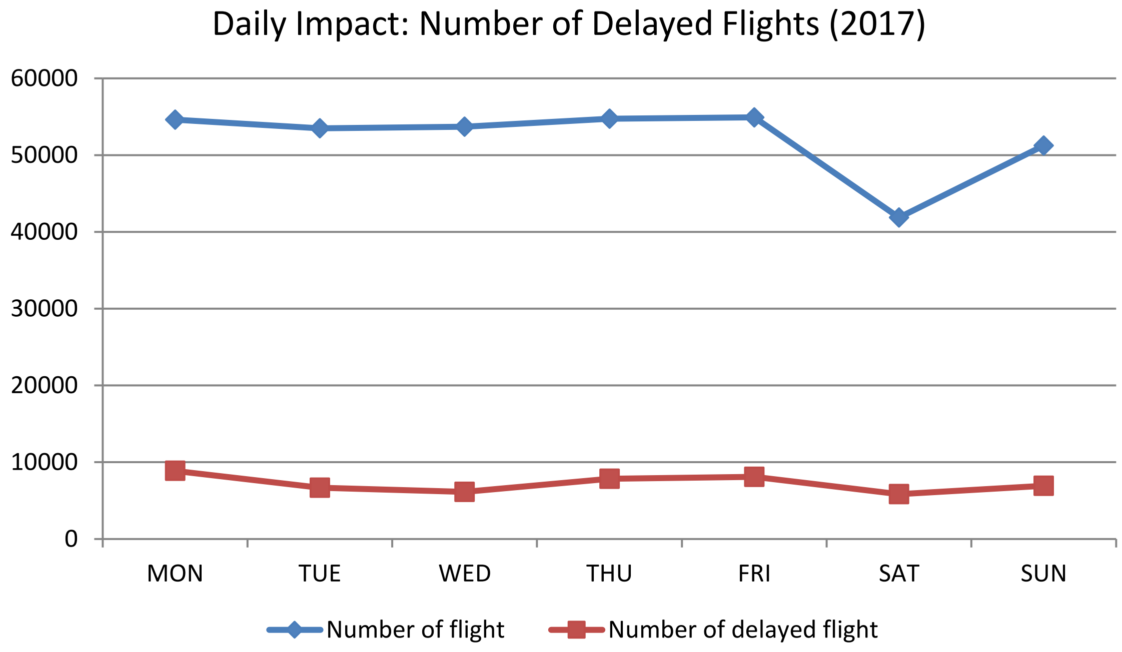


Figure 4-10 Daily Number of Arrived Flight and Delayed Flight in 2017

Figure 4-10 shows the daily record of total flight arrival and how many delayed flights. When looking at the number of flights, Friday has the highest, and Saturday has the lowest. In addition, when looking at the number of delayed flights, Monday has the highest, and Saturday has the lowest. Based on figure 4-10, the possible candidate for the weekends is Friday. Since the feature of the weekends is a large number of flights, Friday is an active representative day.

The representative days should contrast in many ways: the number of flights, and delays. Based on the daily number of flights and delayed flights, the possible candidates are Tuesday and Wednesday. In order to find the reliable day for the weekdays, the total delay time and the delay ratios, which defined in Section 4.1.2.1, will also be checked.

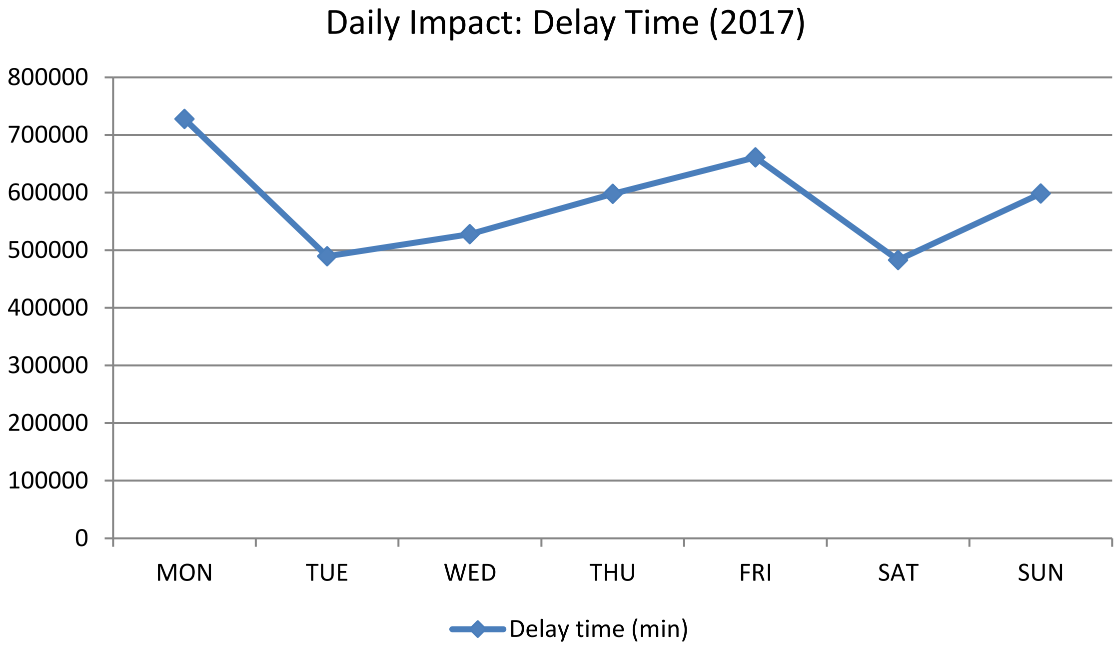


Figure 4-11 Daily Total Delay Time in 2017

Figure 4-11 represents the daily delay time in 2017. When looking at the weekdays, the highest one is Monday, and the lowest one is Tuesday. Likewise, when looking at the weekends, the highest one is Friday, and the lowest one is Saturday. To find the contrast scenario to Friday, Tuesday is a reasonable choice.

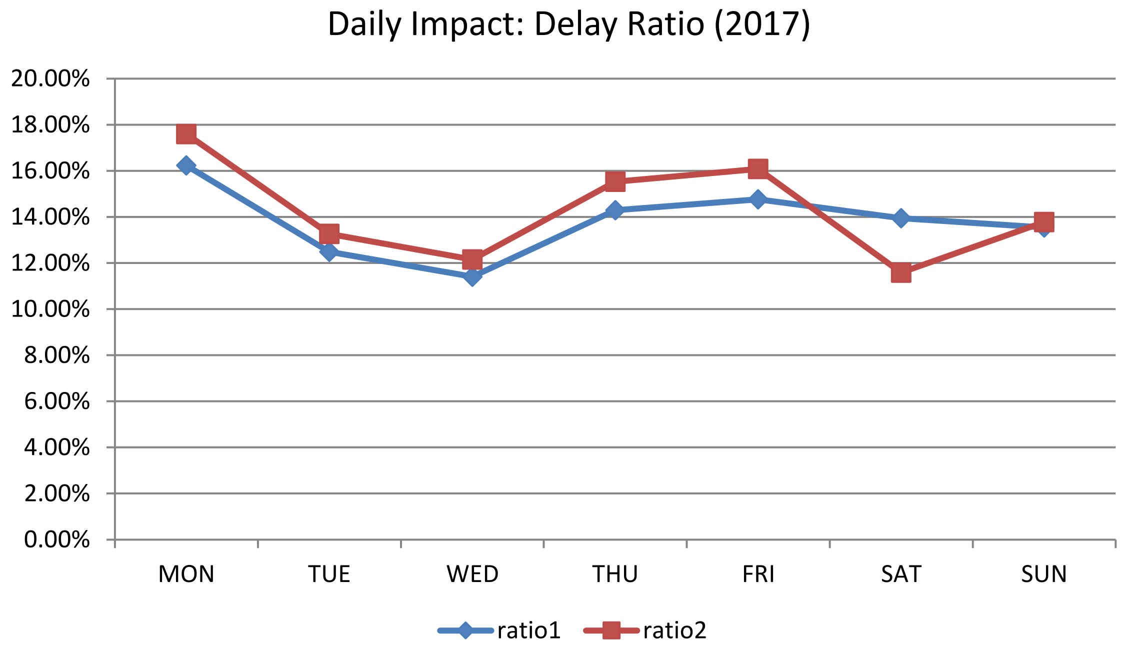


Figure 4-12 Daily Delay Ratios in 2017

Figure 4-12 shows the ratios. There are two ratios would be calculated by the followings:

$$x = number\ of\ flight$$

$$y = number\ of\ delayed\ flight$$

$$ratio1 = \frac{y}{x}$$

$$ratio2 = \frac{y}{\sum y}$$

Based on the ratios, it is hard to select the representative day for the weekdays. Thus, overall, Tuesday is applied to the simulation modeling as the representative day for the weekdays.

Table 4-3 Daily Delay in 2017

Day of Week	Number of Flights ···(a)	Number of Delayed Flights··· (b)	Delay Time (min)	Ratio of Delay (b) / (a)	Ratio of Delay (b) / ∑(b)
Monday	54623	8867	727706	16.23%	17.60%
Tuesday	53486	6683	489672	12.49%	13.26%
Wednesday	53704	6129	527934	11.41%	12.16%
Thursday	54739	7826	597905	14.30%	15.53%
Friday	54923	8105	660978	14.76%	16.08%
Saturday	41873	5840	483033	13.95%	11.59%
Sunday	51248	6942	598388	13.55%	13.78%
Total	364596	50392	4085616		100%

Table 4-3 shows the summary of daily impact with the number of flights, the number of delayed flights, delay time and the ratios. Since Friday has the highest number of flights, it is selected for the representative day for the weekends. Tuesday is selected for the representative day for the weekdays because it is most distinct with respect to Friday.

4.1.3 Summary

The simulation model will run with various operational scenarios, which include the features of the historical data. Thus, in section 4.1, the primary focus is the analysis of flight data and how to use it.

Based on the historical flight arrival data from BTS, the representative months by the level of congestion are selected and the representative days are also selected. The following figure is a summarized view of the operational scenarios.

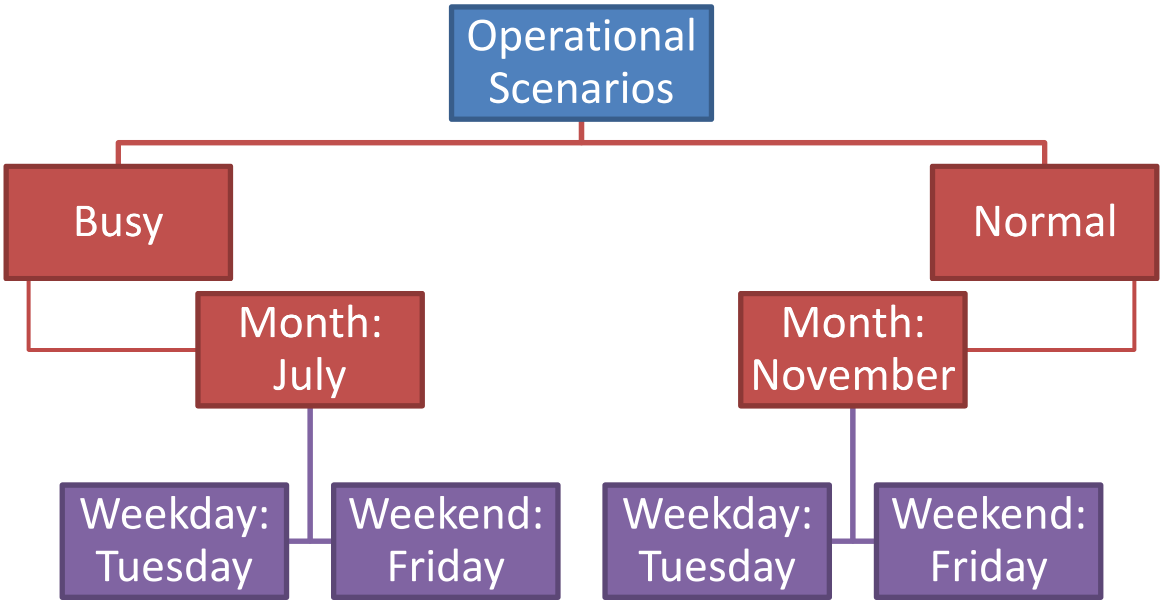


Figure 4-13 Type of Operational Scenarios

4.2 Operational Scenarios

In section 4.1, July is selected for the busy scenario and November is selected for the normal scenario. In order to investigate the resilience of the aircraft turnaround process, the representative day is required. Thus, based on the historical data, Tuesday is selected for the weekdays and Friday is selected for the weekends. Section 4.2 will focus on the features of selected days and show how to use them.

4.2.1 Busy: July

July is the selected month for the busy scenario based on the statistical records, and Tuesday and Friday are picked for the representative days. Thus, in this section, the selected days in July will be introduced with their features.

4.2.1.1 Weekday: Tuesday

Table 4-4 shows the flight records of all Tuesday in July. There are a few numbers of untracked flight in BTS data. It means the flight arrival has been originally scheduled, but not reported the final arrival information due to the cancellation. Thus, it will be excluded from the simulation process.

Table 4-4 Flight Records on Tuesday in July

Date	Total Number of Flight	Number of Untracked Flights	Number of Flights for the Simulation
July 4, 2017	879	0	879
July 11, 2017	1108	5	1103
July 18, 2017	1108	3	1105
July 25, 2017	1108	1	1107

The total number of flights on July 4th is significantly less than the other days. It seems to be caused by Independence Day. It cannot show the feature of the busy season. Thus it will be excluded.

Figure 4-14, 4-15 and 4-16 show the distribution of the flight arrival on Tuesday in July. The size of the bin is 10 minutes. In general, the expected shape of the distribution for the daily flight arrival is bimodal that has one peak in the morning and another peak in the evening. However, the data does not meet the bimodal distribution, but rather a multi-modal distribution that has multiple peaks (more than two).

When looked at the figures, it is clear that the highest peak is formed between 8:20 am and 9:10 am. Also, the soft peaks are formed around 1:00 pm and 8:00 pm.

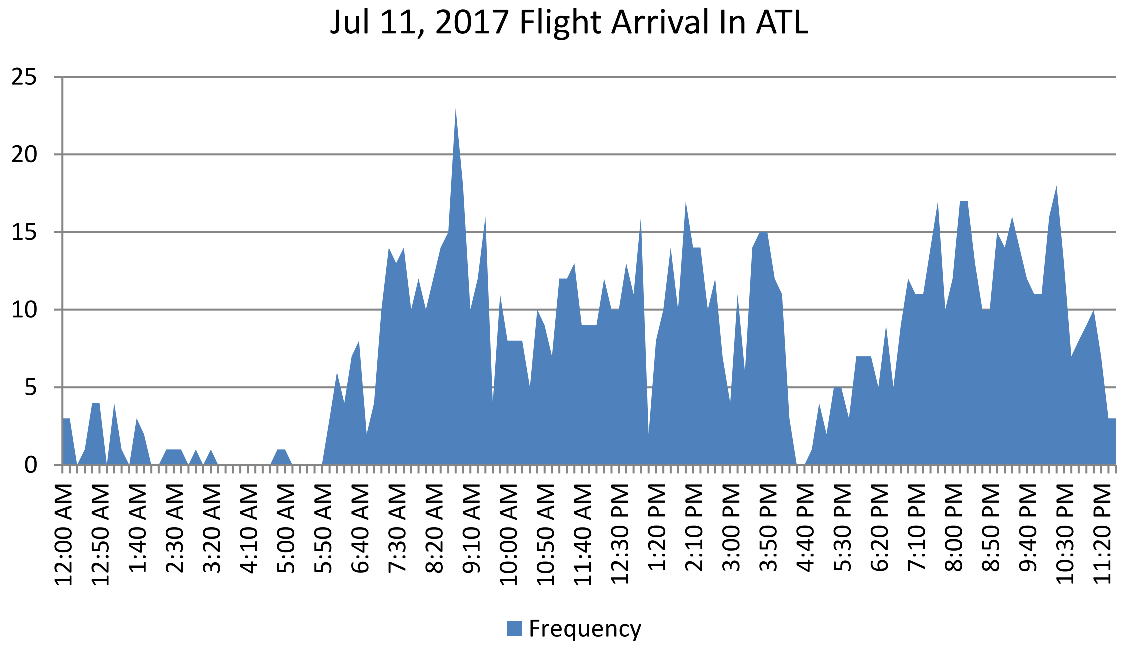


Figure 4-14 Flight Arrival on Tuesday, July 11, 2017

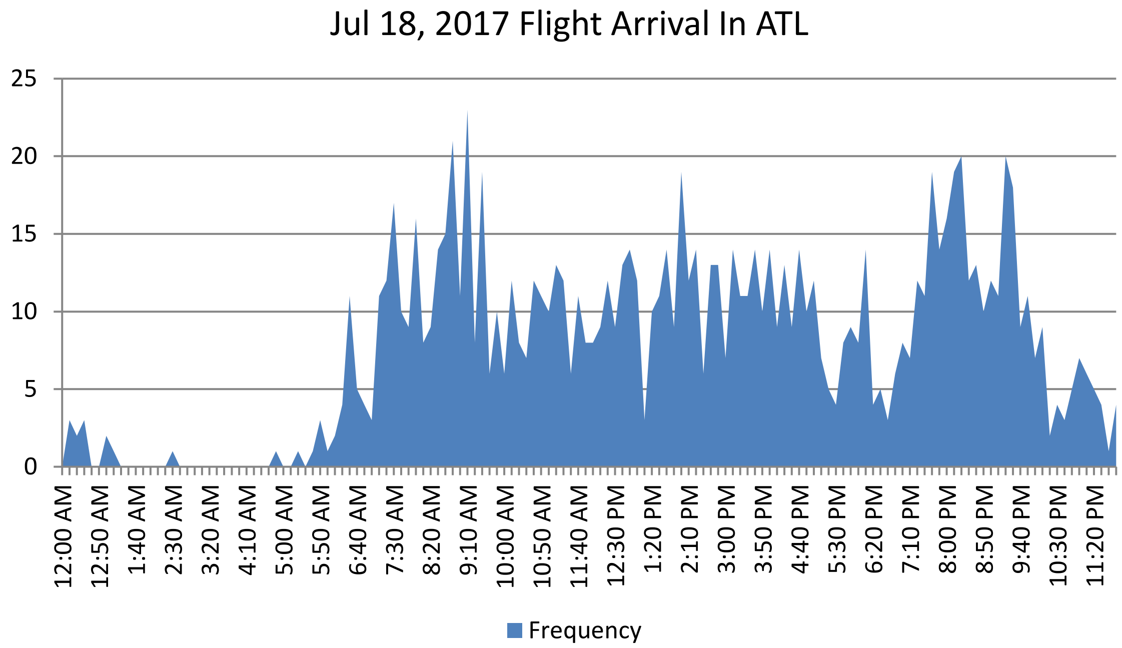


Figure 4-15 Flight Arrival on Tuesday, July 18, 2017

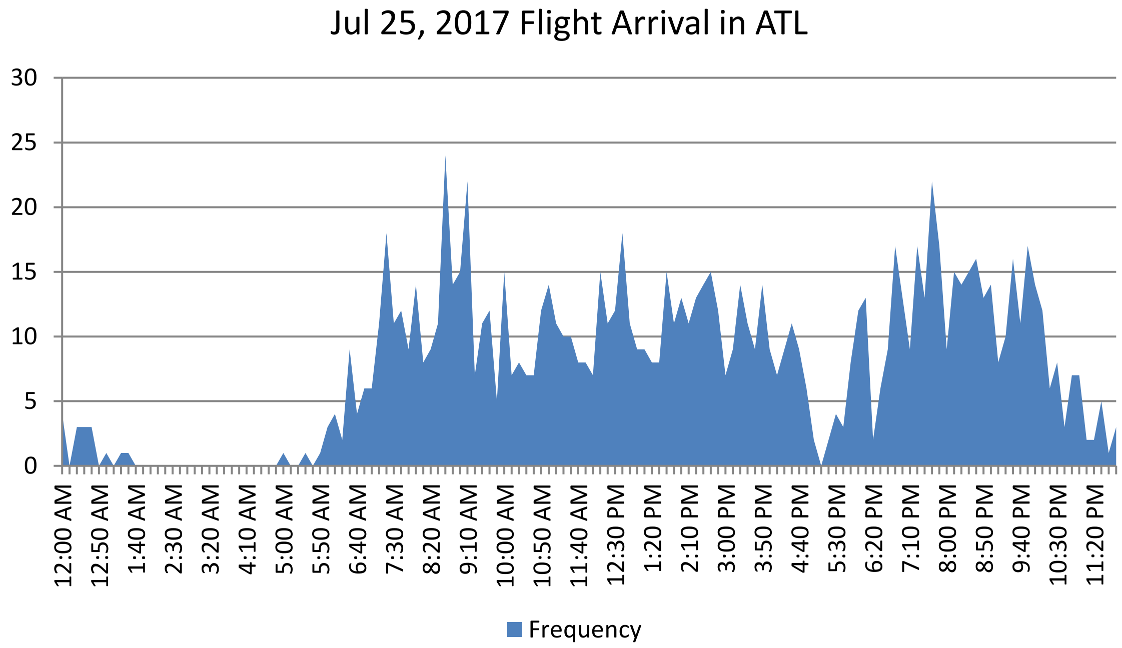


Figure 4-16 Flight Arrival on Tuesday, July 25, 2017

4.2.1.2 Weekend: Friday

Table 4-5 shows the flight records of all Friday in July. Compared to Tuesday in July, it is clear that the number of daily flights is increased. As explained in the previous section, the untracked flights will be excluded.

Table 4-5 Flight Records on Friday in July

Date	Total Number of Flight	Number of Untracked Flights	Number of Flights for the Simulation
July 7, 2017	1031	1	1030
July 14, 2017	1119	7	1112
July 21, 2017	1120	1	1119
July 28, 2017	1115	3	1112

Figure 4-17, 4-18, 4-19 and 4-20 show the distribution of the flight arrival on Friday in July. The size of the bin is 10 minutes as mentioned in section 4.1.2.1. There is no bimodal distribution as well on Friday in July. When looked at the all Friday distribution, it is unclear where the highest peak is formed. However, it shows the morning peak at around 9:00 am. When looked at the afternoon period, there is no standard feature, but most of the distributions show a peak around 8:00 pm.

Figure 4-17 and 4-19 show a similar shape. Also, Figure 4-20 has a similar shape, but the frequency is lower than them. Additionally, Figure 4-18 shows a different shape because of the highest frequency around 10:00 pm.

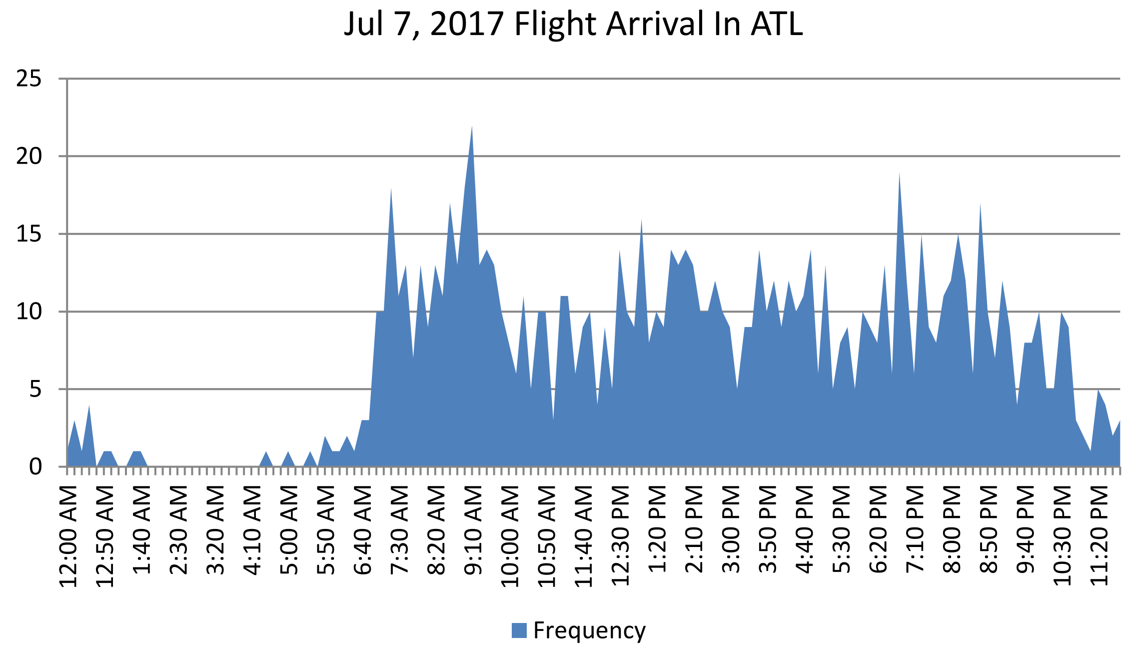


Figure 4-17 Flight Arrival on Friday, July 7, 2017

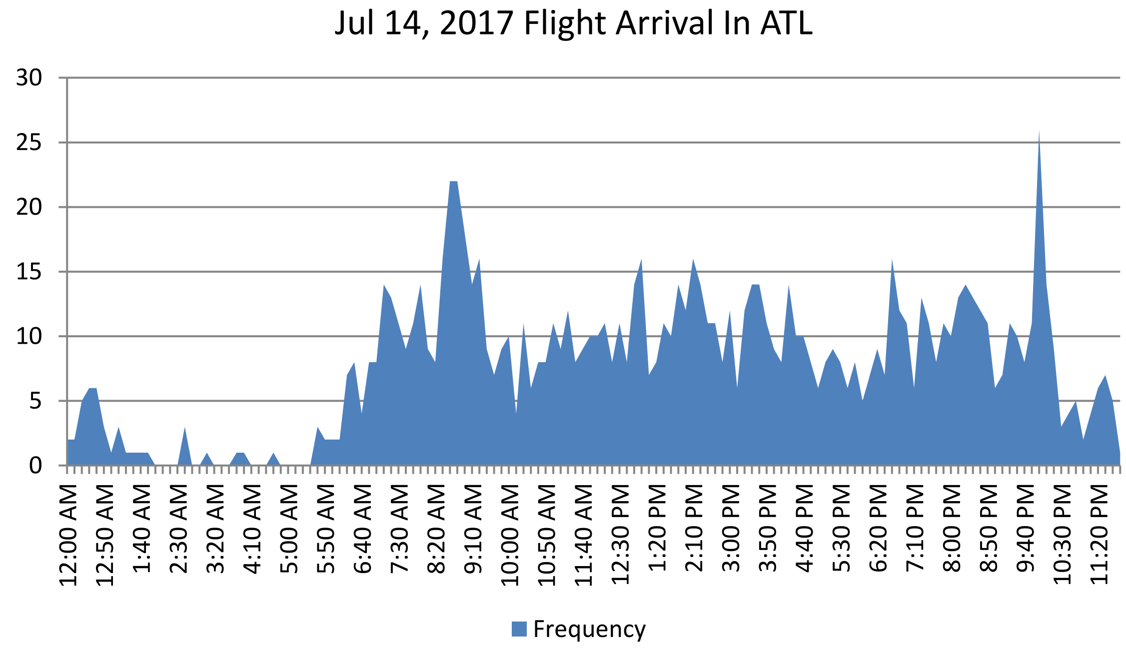


Figure 4-18 Flight Arrival on Friday, July 14, 2017

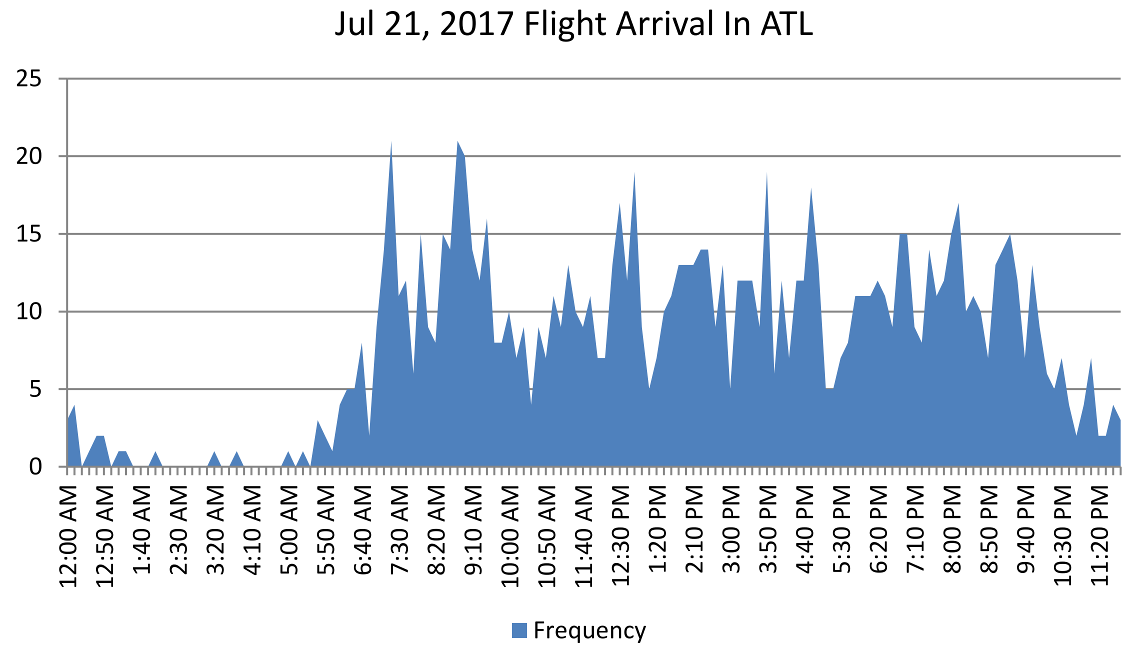


Figure 4-19 Flight Arrival on Friday, July 21, 2017

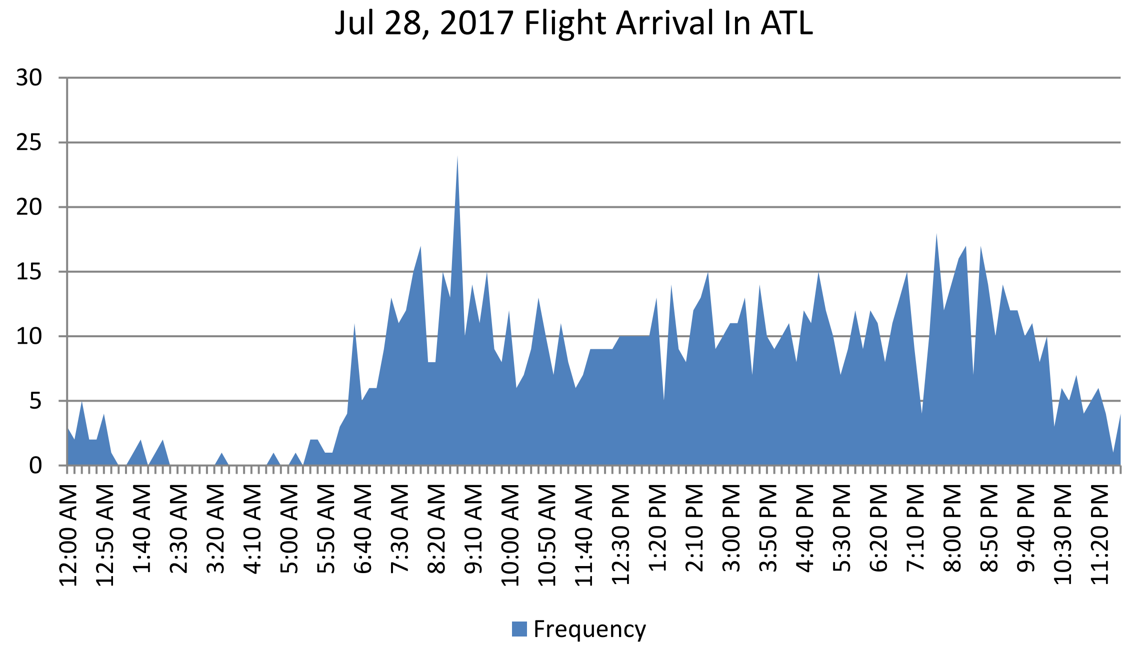


Figure 4-20 Flight Arrival on Friday, July 28, 2017

4.2.2 Normal: November

November is selected for the normal scenario based on the statistical records, and Tuesday and Friday are picked for the representative days. Thus, in this section, the selected days in November will be introduced with their features.

4.2.2.1 Weekday: Tuesday

Table 4-6 shows the flight records of all Tuesday in November. Compared to the representative days in July, it is evident that there is much less daily traffic. As explained, the untracked flights will be excluded from the simulation process.

Table 4-6 Flight Records on Tuesday in November

Date	Total Number of Flight	Number of Untracked Flights	Number of Flights for the Simulation
Nov 7, 2017	951	0	951
Nov 14, 2017	996	0	996
Nov 21, 2017	949	0	949
Nov 28, 2017	958	1	957

Figure 4-21, 4-22, 4-23 and 4-24 show the distribution of the flight arrival on Tuesday in November. The size of the bin is 10 minutes as well. There is no bimodal distribution as well on Tuesday in November.

Figure 4-21 and 4-22 show that the highest peak in the morning time, and figure 4-23 and 4-24 show that the highest peak in the afternoon time.

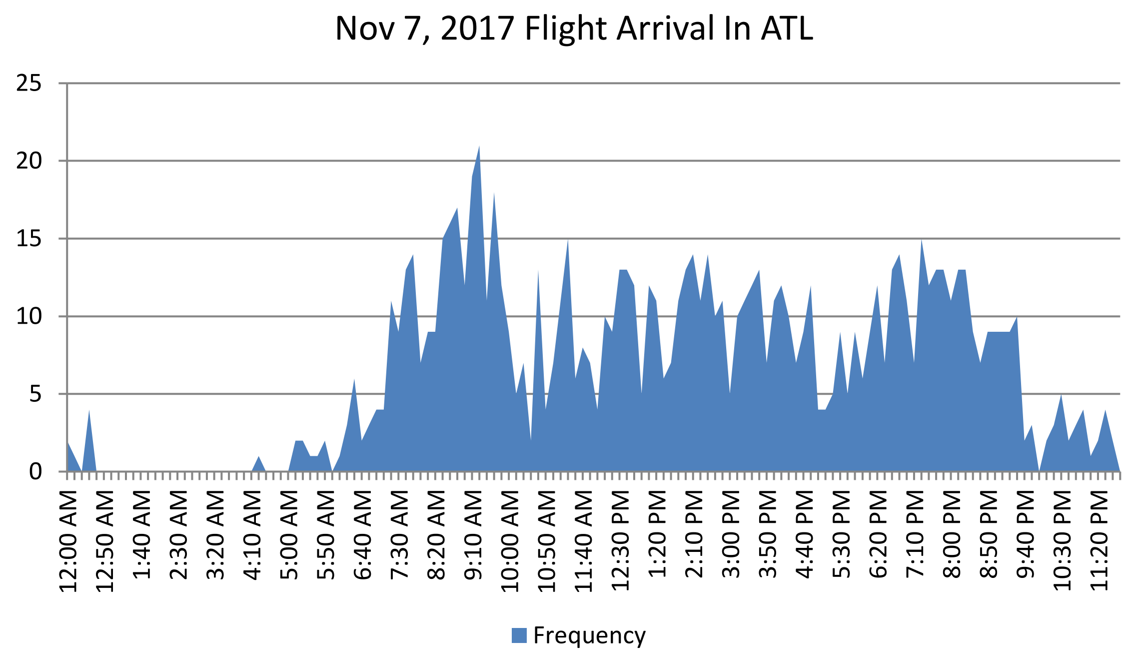


Figure 4-21 Flight Arrival on Tuesday, Nov 7, 2017

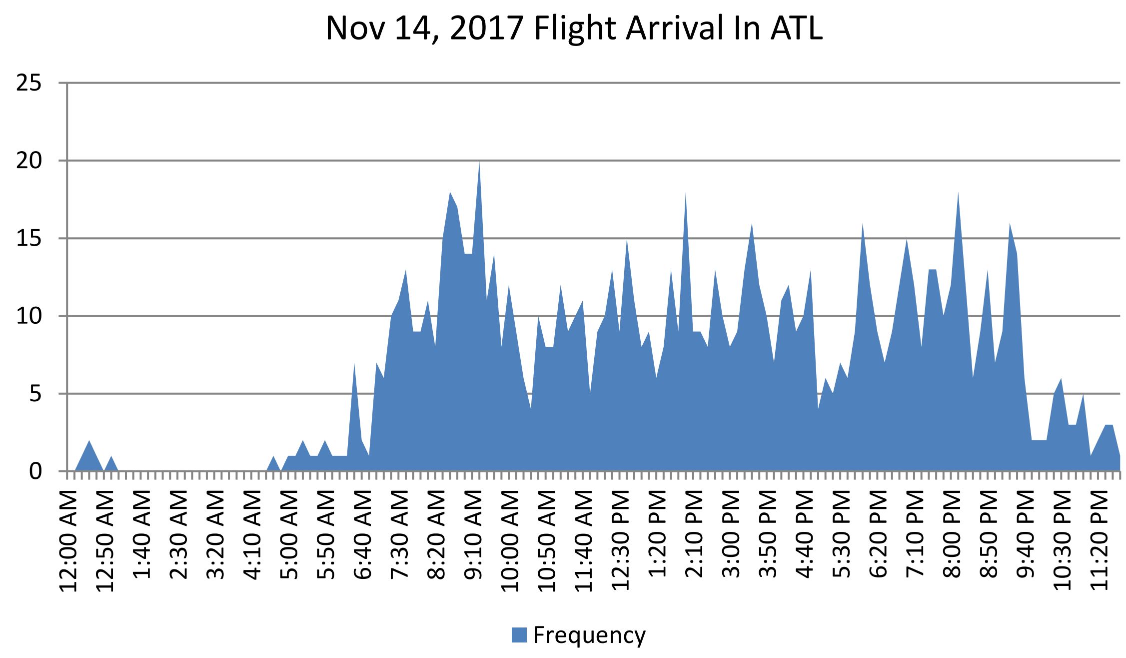


Figure 4-22 Flight Arrival on Tuesday, Nov 14, 2017

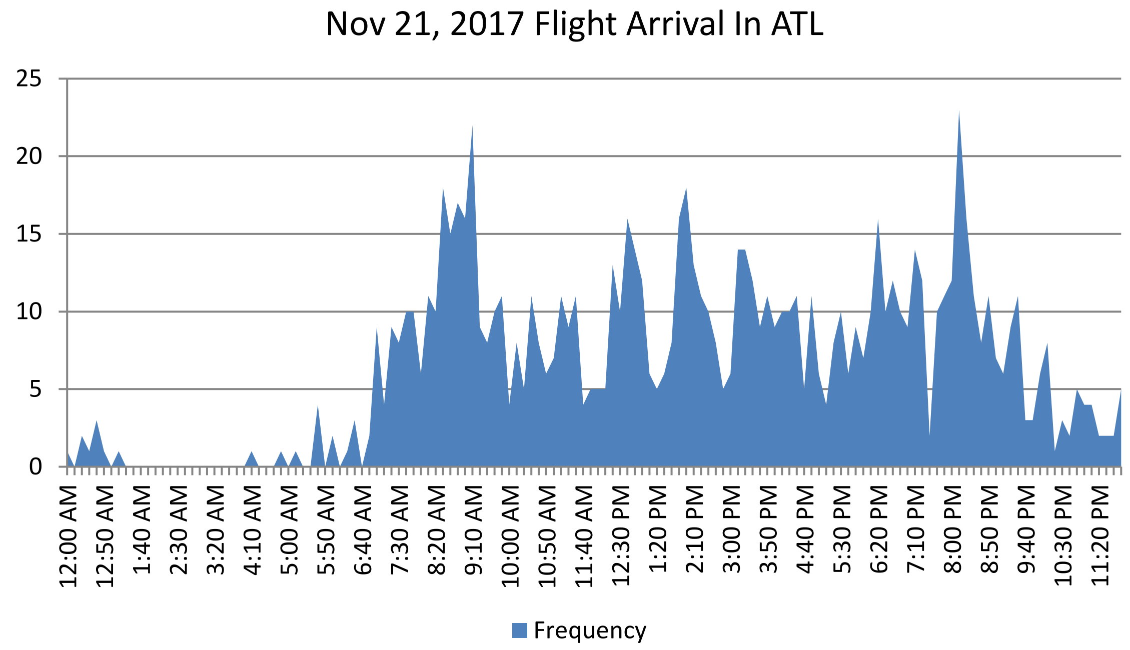


Figure 4-23 Flight Arrival on Tuesday, Nov 21, 2017

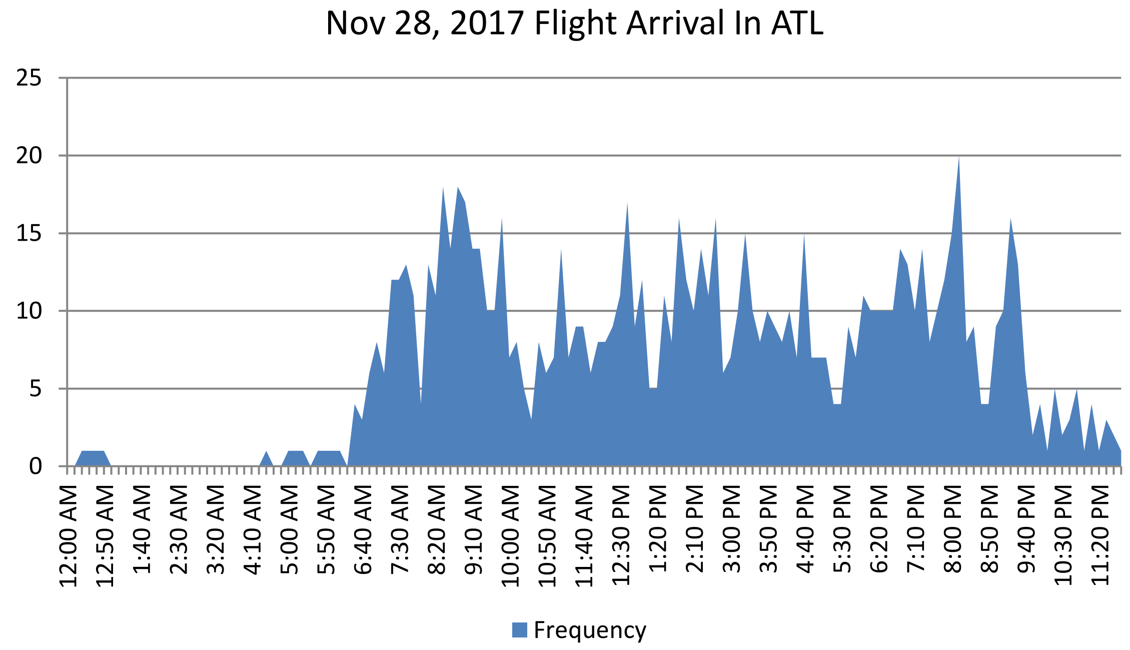


Figure 4-24 Flight Arrival on Tuesday, Nov 28, 2017

4.2.2.2 Weekend: Friday

Table 4-7 shows the flight records of all Fridays in November. The total number of flight on November 24th is less than the other days. It seems to be caused by the Thanksgiving holiday. It does not fit the normal traffic scenario. Thus, it will also be excluded. As explained, the untracked flights will be excluded from the simulation process.

Table 4-7 Flight Records on Friday in November

Date	Total Number of Flight	Number of Untracked Flights	Number of Flights for the Simulation
Nov 3, 2017	968	1	967
Nov 10, 2017	1032	4	1028
Nov 17, 2017	1037	0	1037
Nov 24, 2017	728	0	0

Figure 4-25, 4-26, and 4-27 show the distribution of the flight arrival on Friday in November. The size of the bin is 10 minutes as well. There is no bimodal distribution as well on Friday in November.

Figure 4-25 shows the feature that the highest peak occurs around 1:00 pm. It is the first feature ever observed. Additionally, Figure 4-26 and 4-27 show a similar shape, such as the highest peak in the morning time.

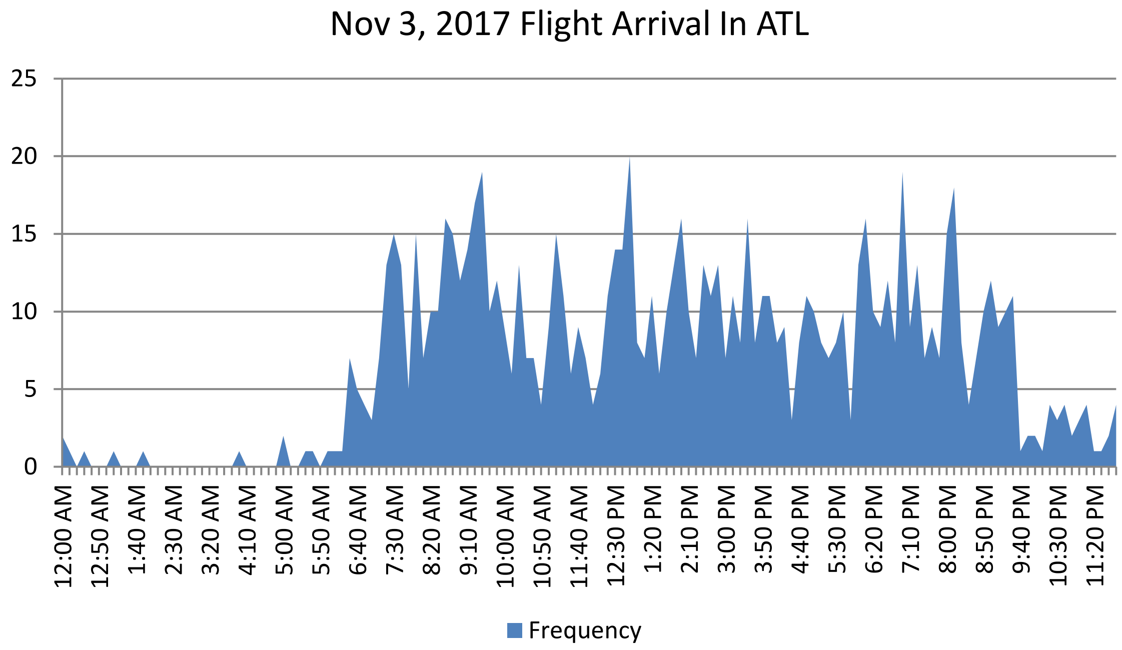


Figure 4-25 Flight Arrival on Friday, Nov 3, 2017

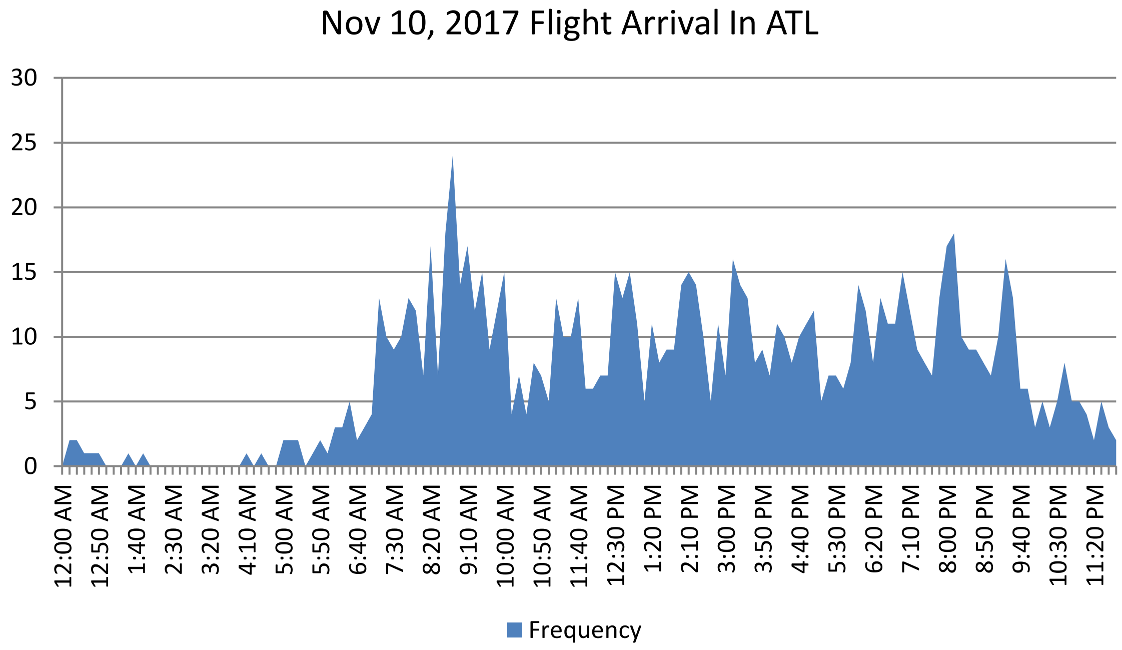


Figure 4-26 Flight Arrival on Friday, Nov 10, 2017

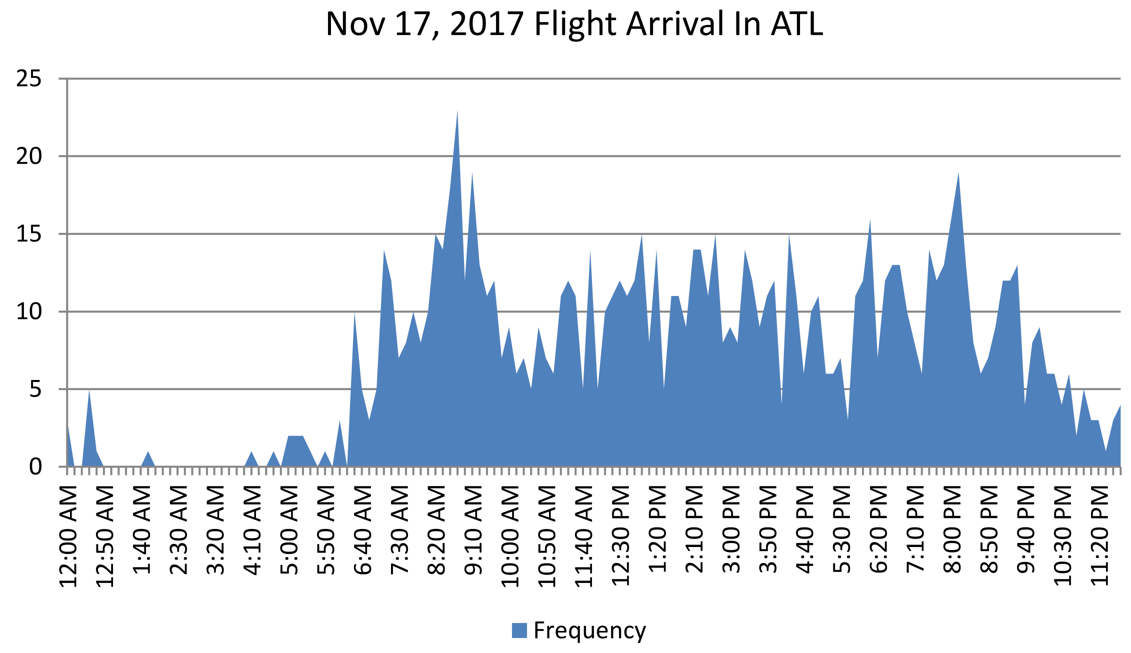


Figure 4-27 Flight Arrival on Friday, Nov 17, 2017

4.2.3 Summary

In section 4.2, the selected days were reviewed to capture their features. The distinct feature is that most of the daily distributions have the highest peak in the morning time and more peaks in the afternoon time.

First, it was checked whether the selected day is a special holiday or not. Special days are excluded from the review. Then, every distribution will be the input scenario for the flight arrival in the simulation process. Some flights look like an outlier in the daily distribution, but will still be included in the input scenario because it is necessary to handle the unexpected situation in the airport. Figure 4-28 shows the final set of operational scenarios. In the simulation process, every option will have the same probability to occur at the same level.

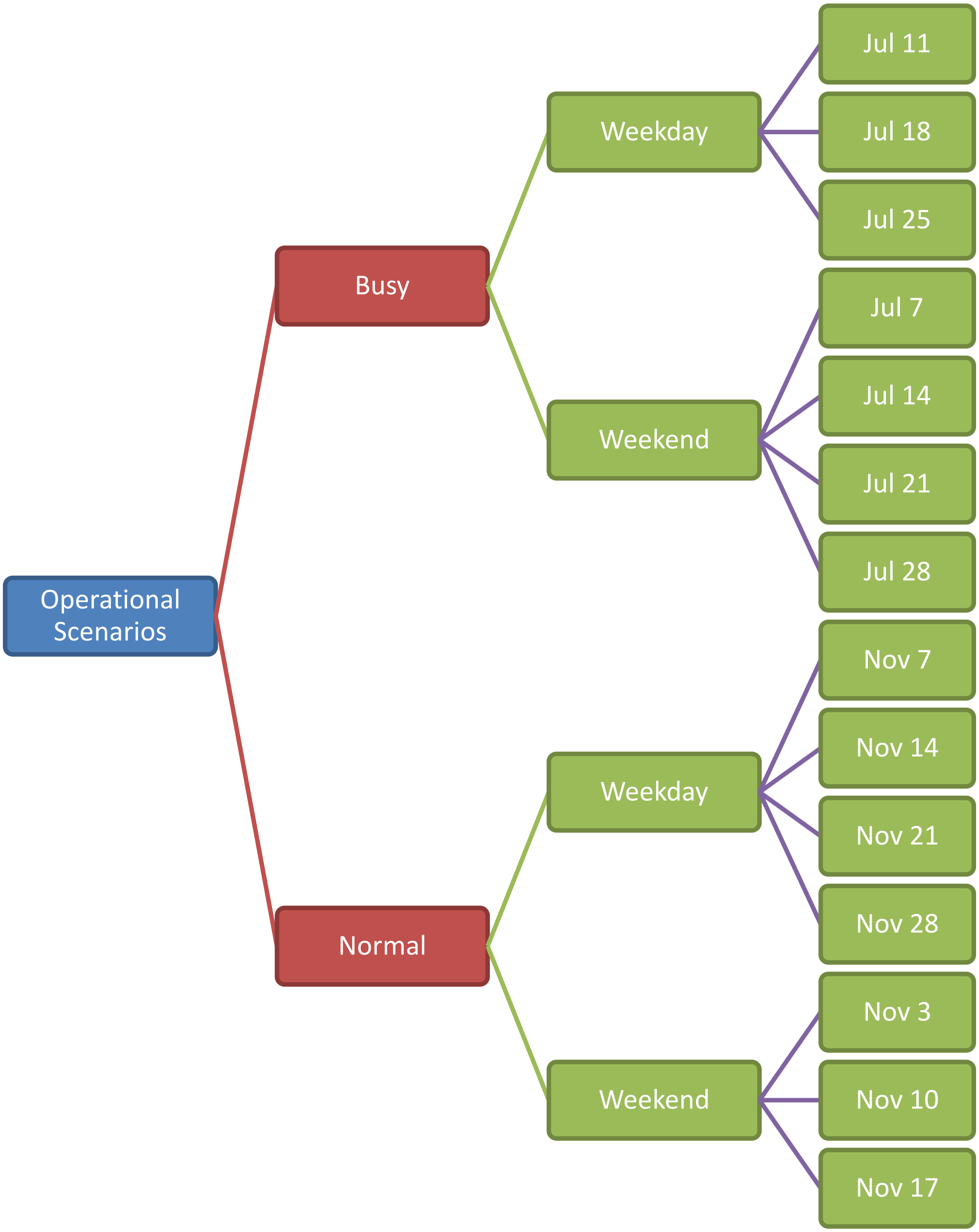


Figure 4-28 Operational Scenarios for Simulation Modeling

4.3 Turnaround Process and Time

In section 4.1 and 4.2, the primary focus is the analysis of historical data in order to set the operational scenarios and find their features. Thus, it can be assumed that the flight arrival schedule is defined now by the operational scenarios.

When the aircraft arrives at the airport, it should prepare for the next departure. For the next departure, the turnaround process is a necessary and sufficient step.

In section 2.1, it is already discussed about the definition of aircraft turnaround process and their time. Thus, in this section, it is required to approach the aircraft turnaround process must be included as an input of the simulation process. Therefore, the primary issue of this section is the actual turnaround time.

Based on section 2.1, every aircraft has a minimum turnaround time by their type. It means aircraft type is a critical factor to set the turnaround time in the simulation process. Thus, the number of net orders and deliveries will be considered to select the aircraft type.

Table 4-8 shows the top nine aircraft sorted by the number of net orders by historical records. To calculate the turnaround process time, one of the critical factors is the number of passengers.

When looking at the usual number of seats, it has various ranges. Thus, the top nine aircraft are reasonable inputs. The turnaround time of these aircraft will be reviewed, and the standard format of the process will be defined for the simulation. Additionally, A220 is ranked seven in the list, but there is no manual for that. Thus, it will be excluded.

Table 4-8 Popular Aircraft in the World [69]

Model	Net Orders	Deliveries	MTOW(t)	Seats	Range
Airbus A320	13160	7658	68-95	107-206	3,110-4,000
Boeing 737	10660	6257	70.1-88.3	126-188	2,935-3,515
Airbus A330	1631	1329	242	247-287	6,350-7,500
Boeing 777	1369	944	347.5-351	301-400	7,370-8,700
Boeing 787	1265	591	227.9-250.8	242-330	6,430-7,635
Airbus A350	856	114	259-308	276-366	7,950-8,245
Airbus A220	355	18	60.8-67.6	108-130	3,100-3,300
Airbus A380	317	216	575	544	8,200
Boeing 747	124	110	137.7	410-605	8000

4.3.1 Boeing

In table 4-8, four types of Boeing aircraft named on the list: Boeing 737, Boeing 777, Boeing 787, and Boeing 747. Thus, in this section, the turnaround information in the aircraft manual will be introduced and explained.

4.3.1.1 Boeing 737 Family

The 737 is a twin-engine aircraft. It covers short to medium ranges [70]. According to the 737 Airplane Characteristics for Airport Planning [70] by Boeing, the critical features to airport planners are described as follows:

- Allow the optional airstairs if loading bridges or stairs are not available
- Allow single-station pressure to fuel
- Supply energy with auxiliary power unit: engine starting and air conditioning
- Use standard ground equipment for all service of the 737

The latest derivative in the 737 family will be examined: 737-600, -700, -800 and -900. Table 4-9 shows the model's length and a possible number of passengers.

Table 4-9 737 Family

Boeing 737	Number of Passengers
-600	Up to 130
-700	Up to 148
-800	Up to 184
-900	Up to 189

At first, the standard features of the B737 family are reviewed here. Figure 4-29, 4-30, 4-31 and 4-32 shows the turnaround process of B737 family. It assumes a 100% load factor, and 100% passenger and cargo exchange. Regarding passenger loading rates, the de-boarding rate for passengers is 18 per minute, and the boarding rate for passengers is 12 per minute. Also, it assumes every passenger has one bag. Thus, regarding the luggage loading rates, the luggage loading speed is ten bags per minute, and the unloading speed is 15 bags per minute. Regarding the service, it uses one galley truck. When it works the refueling process, it allows 2700 gallons at 300 gallons per minute and one nozzle at 50 pounds per square inch gauge. It assumes 1,000 gallons fuel reserve.

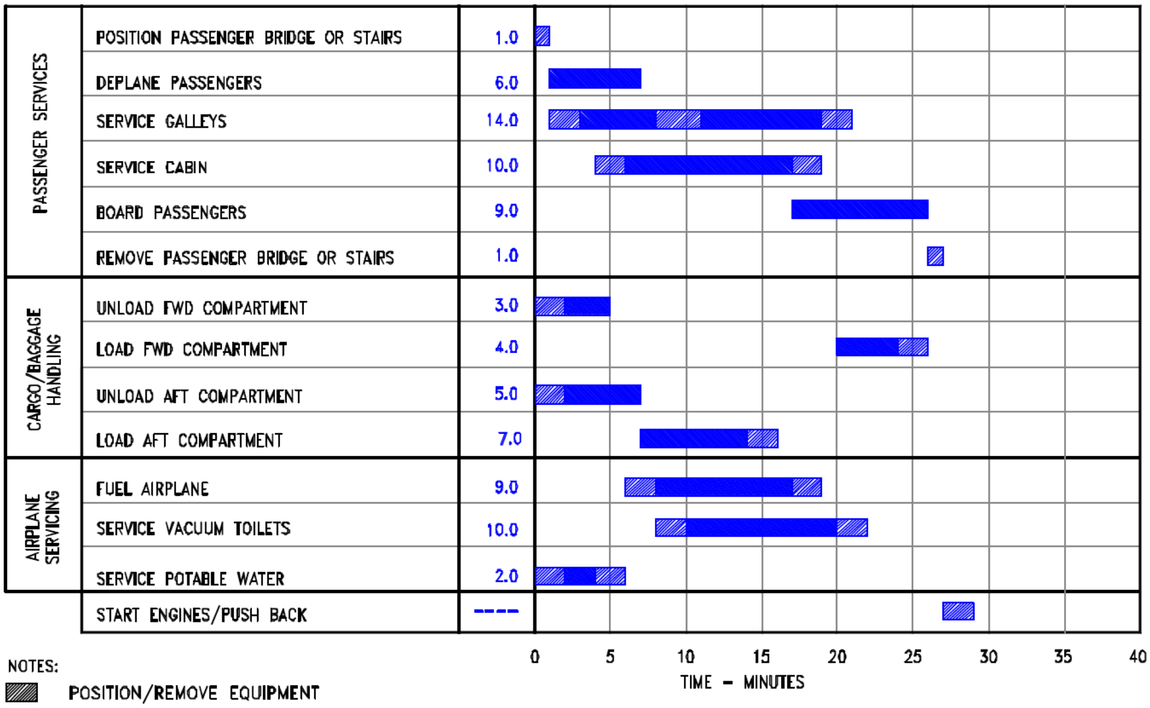


Figure 4-29 Turnaround Process of B737-600 [70]

Figure 4-29 shows the turnaround process of B737-600's turnaround process. It assumes 108 passengers do boarding and de-boarding via the left entry doors. It means there are a total of 108 bags for the flight. Forward compartment handles 38 bags, and aft compartment handles 70 bags.

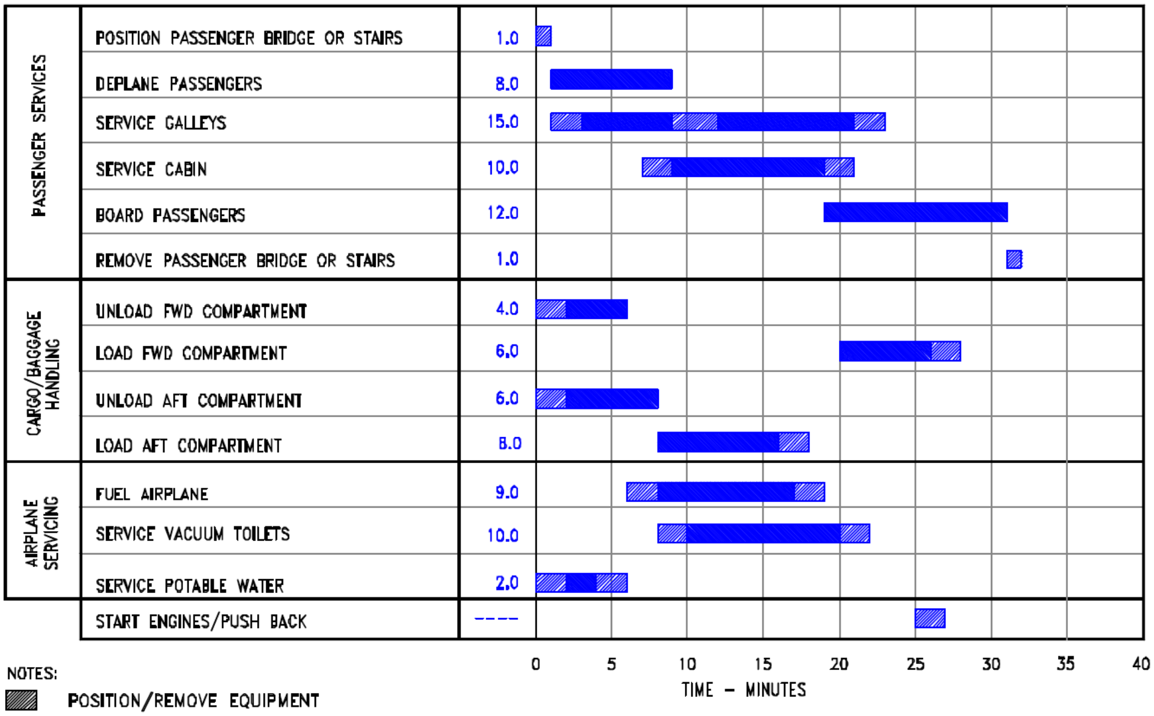


Figure 4-30 Turnaround Process of B737-700 [70]

Figure 4-30 shows B737-700's turnaround process. It assumes 140 passengers do boarding and de-boarding via forward left entry doors. Thus, there are a total of 140 bags for the flight. Forward compartment handles 57 bags, and aft compartment handles 83 bags.

Figure 4-31 shows B737-800's turnaround process. It assumes 160 passengers do boarding and de-boarding via forward left entry doors. Thus, there are a total of 160 bags for the flight. Forward compartment handles 69 bags, and aft compartment handles 91 bags.

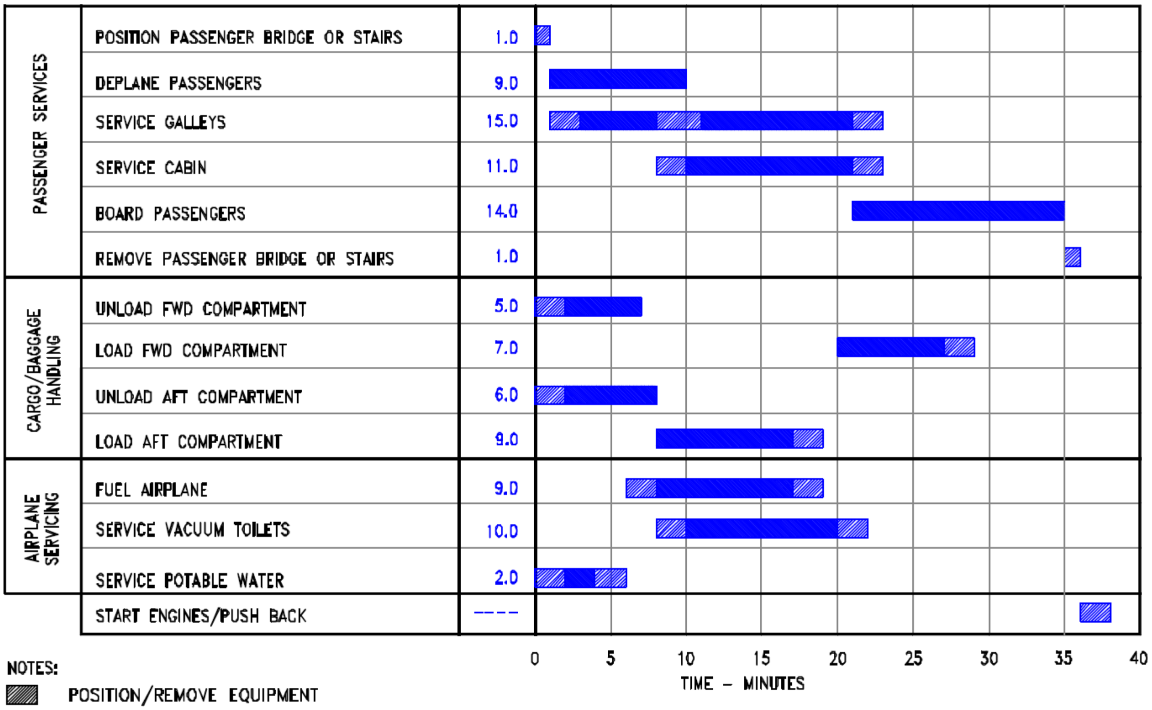


Figure 4-31 Turnaround Process of B737-800 [70]

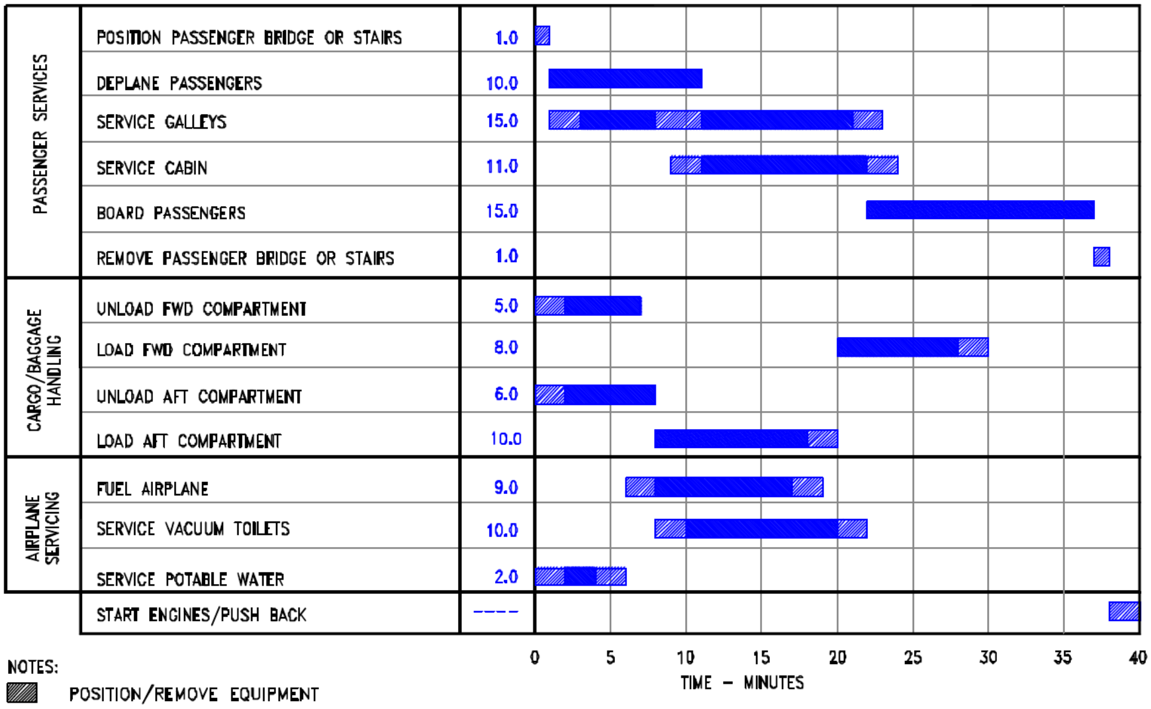


Figure 4-32 Turnaround Process of B737-900 [70]

Figure 4-32 shows B737-900’s turnaround process. It assumes 177 passengers do boarding and de-boarding via forward left entry doors. Thus, there are a total of 177 bags for the flight. Forward compartment handles 80 bags, and aft compartment handles 97 bags.

4.3.1.2 Boeing 777 Family

The 777 family is a twin-engine aircraft. It covers for medium to long range flights [71]. The 777-200 series is the first-generation derivative, and the 777-300 series is a second-generation derivative. The 777-200LR and -300ER will be examined in this section. The 777-200LR is a derivative of the 777-200 aircraft, and the 777-300ER is a derivative of the 777-300 aircraft [71]. Both aircraft are equipped with raked wingtips to provide additional cruise altitude and range.

According to the 777 Airplane Characteristics for Airport Planning by Boeing, the critical feature to airport planners is described as followings:

- If the APU is used, electrical pneumatic and air conditioning trucks are not required.
- Pneumatic cart moves into the position after the air conditioning truck is moved (See Figure 4-33).

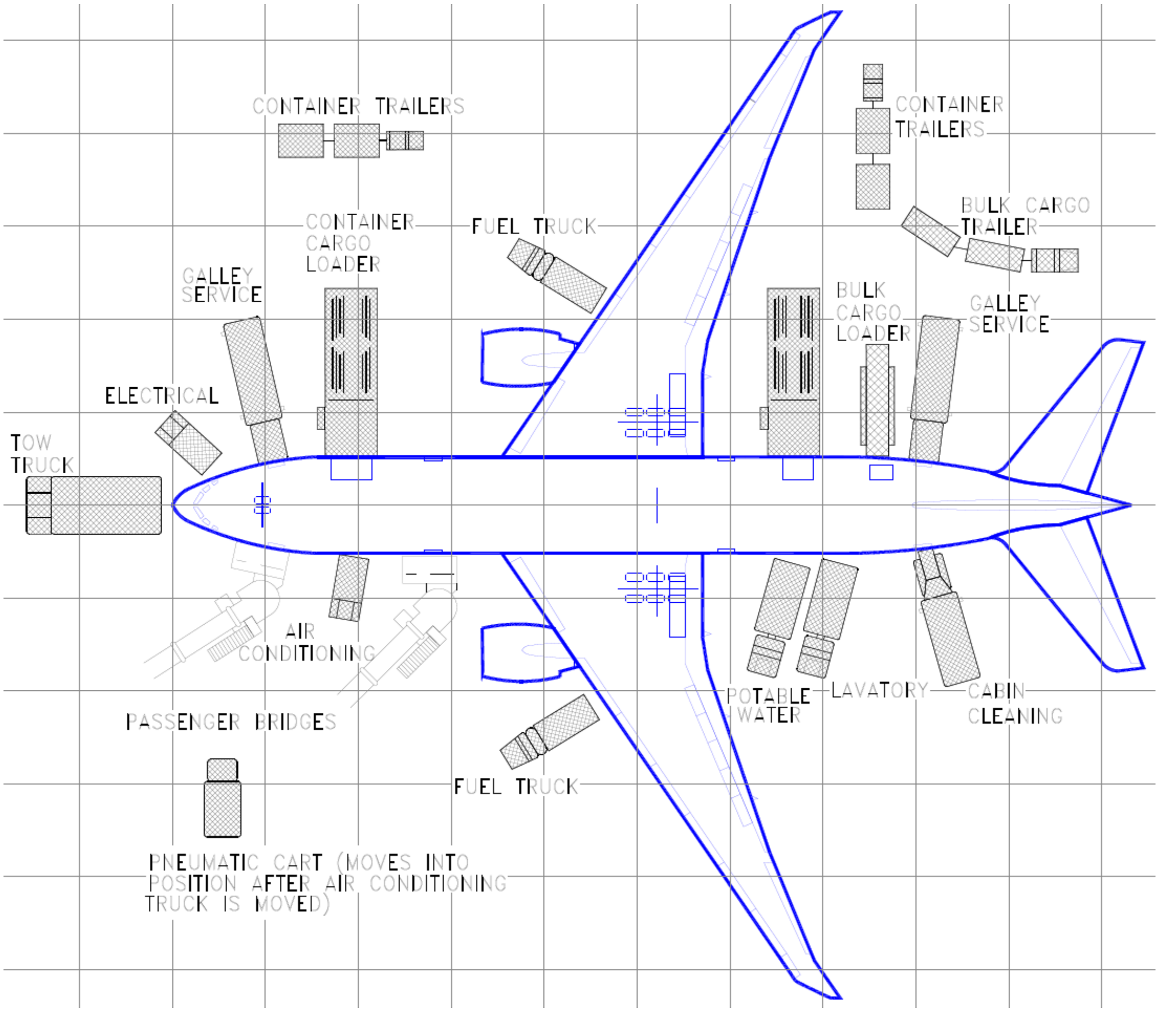


Figure 4-33 Servicing Arrangement of B777-200LR [71]

The standard features of the B737 family are explained here. Figure 4-34 and 4-35 shows the turnaround process of the family. It assumes a 100% load factor, and 100% passenger and cargo exchange. Regarding passenger loading rates, the de-boarding rate for passengers is 50 per minute, and the boarding rate for passengers is 30 per minute. Regarding the service, it uses one galley truck. When it works the refueling process, it allows four nozzles at 50 PSIG and refuels from reserve level of 3700 fuel in main tanks.

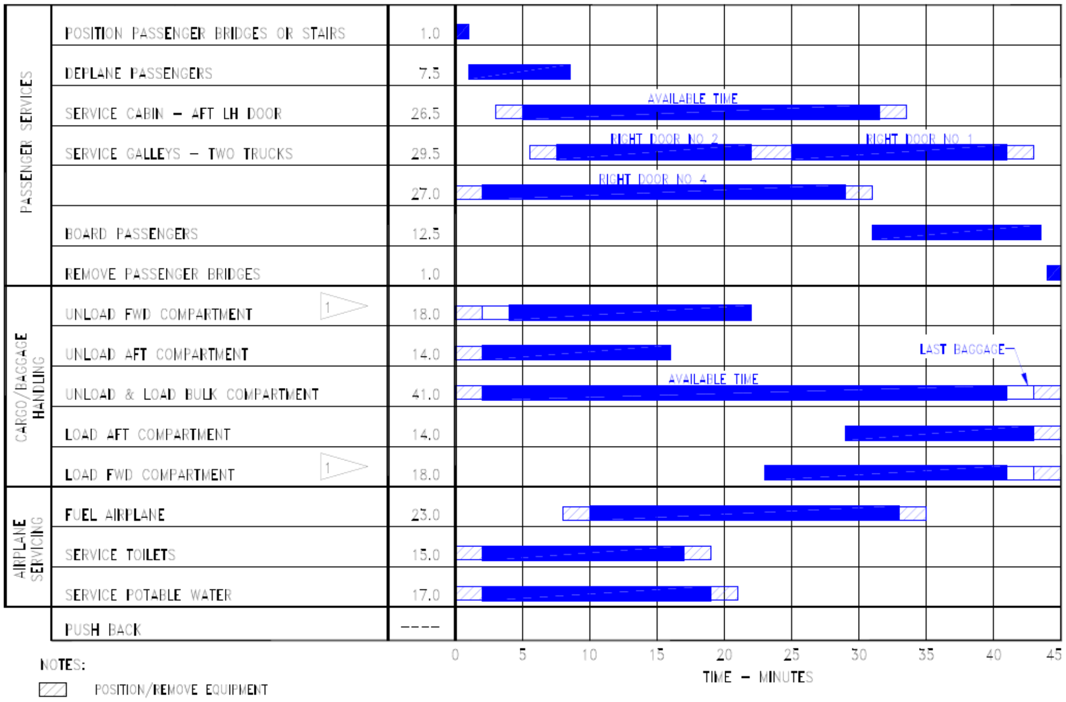


Figure 4-34 Turnaround Process of B777-200LR [71]

Figure 4-34 shows the turnaround process of B777-200LR. It assumes 375 passengers do de-boarding and boarding via two left doors.

Regarding the unloading and loading forward compartment for luggage handling, the defined unloading/loading forward compartment time is 18 minutes. However, the load or unload time is estimated to be 12 minutes if there are six pallets. Luggage operations and refueling sequenced to maintain favorable weight and balance condition. The total aircraft fuel equals 31,600 US GALLON.

Figure 4-35 shows the turnaround process of B777-300ER. It assumes 451 passengers do de-boarding and boarding via two left doors. Regarding the unloading and loading forward compartment for luggage handling, the defined unloading/loading forward compartment time is 24 minutes. However, the load or unload time is estimated to be 16 minutes if there are eight pallets. Regarding the refueling process, the total aircraft fuel equals 45,220 US GALLON.

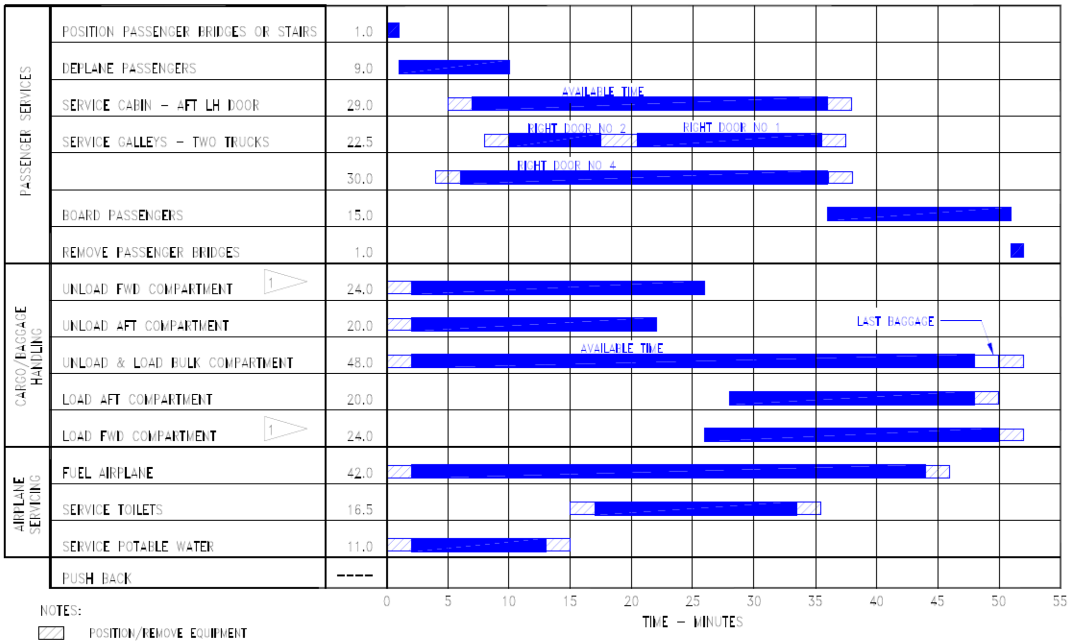


Figure 4-35 Turnaround Process of B777-300ER [71]

Since the figure 4-34 and 4-35 has a low-quality issue from Boeing's original source [71], the table 4-10 shows the turnaround activity time value again.

Table 4-10 Boeing 777 Family Turnaround Activity Time [71]

Activity	B777-200LR (min)	B777-300ER (min)
Position Pax Bridge	1	1
Deplane Passengers	7.5	9
Service Cabin-AFT LH DOOR	26.5	29
Service Galleys-1st truck	29.5	22.5
Service Galleys-2nd truck	27	30

Board Passengers	12.5	15
Remove Pax Bridge	1	1
Unload FWD Compartment (pallets)	18 (12)	24 (16)
Unload AFT Compartment	14	20
Unload and Load Bulk Compartment	41	48
Load AFT Compartment	14	20
Load FWD Compartment (pallets)	18 (12)	24 (16)
Fuel Airplane	23	42
Service Toilets	15	16.5
Service Portable Water	17	11
Pushback	NaN	NaN

4.3.1.3 Boeing 787 Family

The 787 Dreamliner is used to cover medium to long range flights. The 787 family is twin-engine airplanes. It has an exceptional environmental performance and new passenger-pleasure components [72].

According to the 787 Airplane Characteristics for Airport Planning [72] by Boeing, the critical features to airport planners are described as followings:

- The 787 family get a more-electric design
- It does not have a traditional pneumatic system:

  - The traditional pneumatic starters on the engines are replaced with a pair of gearbox-mounted main-engine starter/generators.
  - Cabin air conditioning and wing anti-ice systems are also electrically driven.
  - The remaining pneumatic system is for engine nacelle anti-ice.
- It has ground service connections compatible with existing ground service equipment, and no special equipment is necessary.
- In the case of an inoperable APU, engine starts may be accomplished via the airplane's external ground electrical connections.

In this section, the 787-8, -9, and -10 will be examined. The 787-8 can carry up to 242 passengers in a typical dual-class configuration. The 787-9 can seat up to 290 passengers in a dual-class configuration. The 787-10 can carry as many as 330 passengers in a dual-class configuration.

Here are the standard features of the B787 family. Figure 4-36, 4-37, and 4-38 shows the turnaround process of B787 family. It assumes a 100% load factor, and 100% passenger and cargo exchange. Regarding passenger loading rates, the de-boarding rate for passengers is 40 per minute, and the boarding rate for passengers is 25 per minute. Regarding the service, it uses two galley trucks, one lavatory service truck, and one potable water service truck.

The distinct features of B787 are given in the followings: available time service and critical path. The manual assumes cabin service and unloading/loading bulk cargo is done in available time and the available time is up to aircraft type. In the previous section, the manufacturer's document for the 737 family and the 777 family were reviewed. The critical path did not appear in there. However, the 787 family has a critical path for the cargo/luggage handling. The unloading activity should be pre-processed before the loading process. Also, there is no break between unloading and loading via the forward compartment. The available time for unloading/loading bulk cargo is a time frame of the forward and aft compartment.

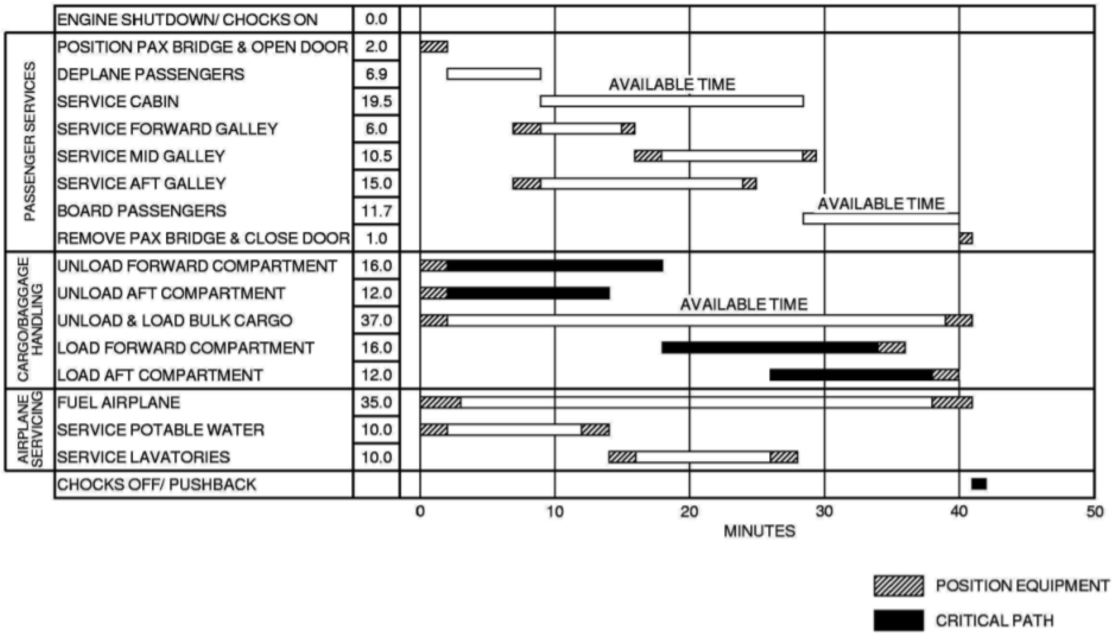


Figure 4-36 Turnaround Process of B787-8 [72]

Figure 4-36 shows the turnaround process of B787-8. It assumes a total of 274 passengers from two classes do de-boarding and boarding via one door. When it works the refueling process, it allows 29,798 gallons fuel loaded with 3,730 gallon reserve and uses four nozzles hydrant fueling at 50 PSIG.

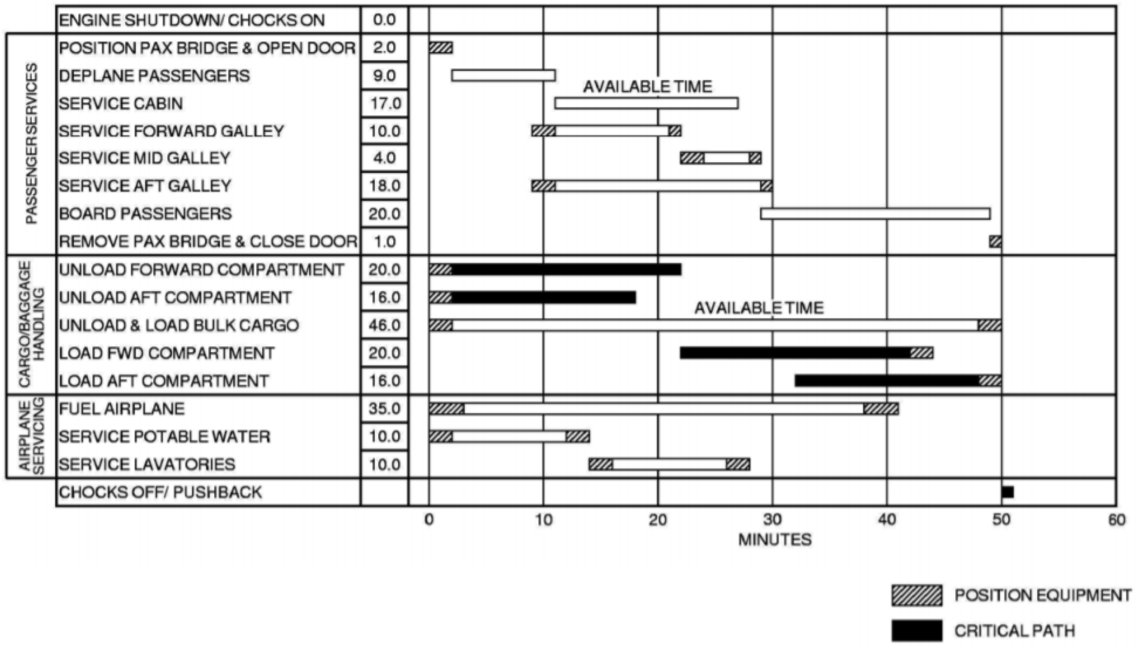


Figure 4-37 Turnaround Process of B787-9 [72]

Figure 4-37 shows the turnaround process of B787-9. It assumes a total of 360 passengers from two classes do de-boarding and boarding via one door. When it works the refueling process, it allows 29,654 gallons fuel loaded with 3,730-gallon reserve and four nozzles hydrant fueling at 50 PSIG.

Figure 4-38 shows the turnaround process of B787-10. It assumes a total of 411 passengers from two classes do de-boarding and boarding via one door. When it works the refueling process, it allows 29,654 gallons fuel loaded with 3,730-gallon reserve and two nozzles hydrant fueling at 50 PSIG.

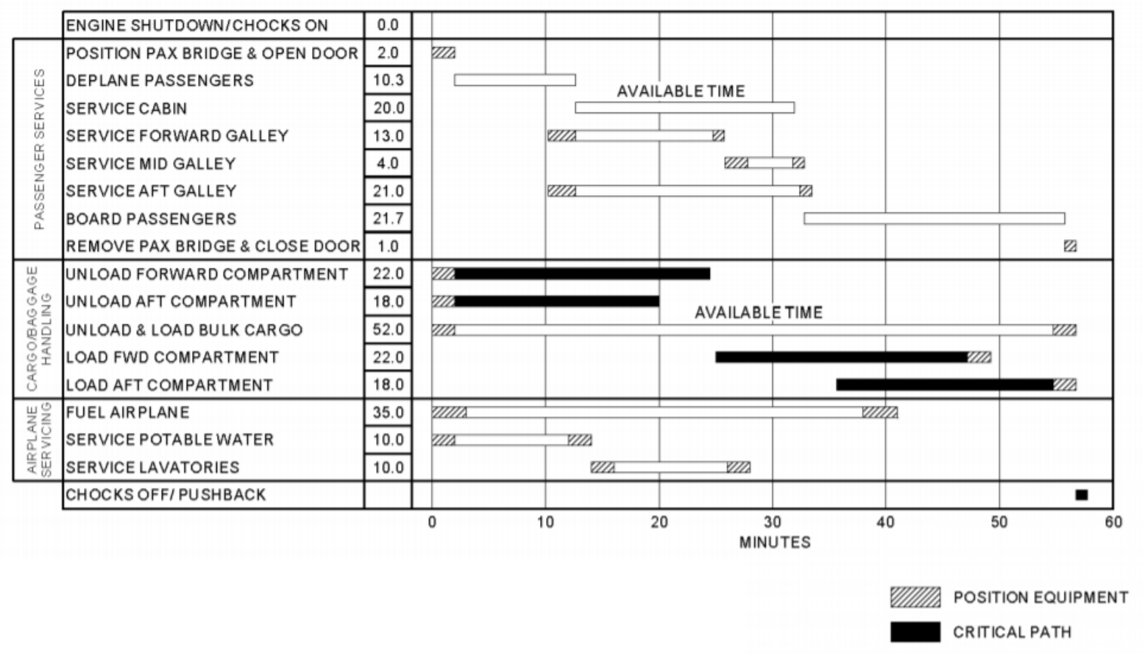


Figure 4-38 Turnaround Process of B787-10 [72]

4.3.1.4 Boeing 747 Family

The 747 family is wide-body aircraft that covering for short to long ranges. Since the 747-400 is the latest derivative of the 747, the 747-400 series will be focused in this section, especially for airliners. The basic 747-400 has a tri-class passenger interior arrangement, but there are the voluntary arrangements including a two-class or a one-class configuration to suit traffic demands [73]. Additionally, it has optional fuel tanks in the forward cargo compartment and horizontal stabilizer.

Figure 4-39 and 4-40 shows the turnaround process of B747-400ER, -400, -400 Combi, and -400 Domestic. Here are the standard features of the B747-400 series. It assumes a 100% load factor, and 100% passenger and cargo exchange. Regarding passenger loading rates, the de-boarding rate for passengers is 40 per minute, and the boarding rate for passengers is 25 per minute. Regarding the service, it uses three galley trucks and one lavatory service truck. The cabin service is time available between passenger exchanges.

Figure 4-39 shows the turnaround process of B747-400ER. It assumes 442 passengers do de-boarding and boarding via one door. When it works the refueling process, it allows 55,800 gallons fuel loaded with 4,200 gallons reserve and uses four nozzles hydrant fueling at 35 PSIG. Regarding the supplying water process, it requires potable water 440 gallons at 10 GPM and 60 PSIG.

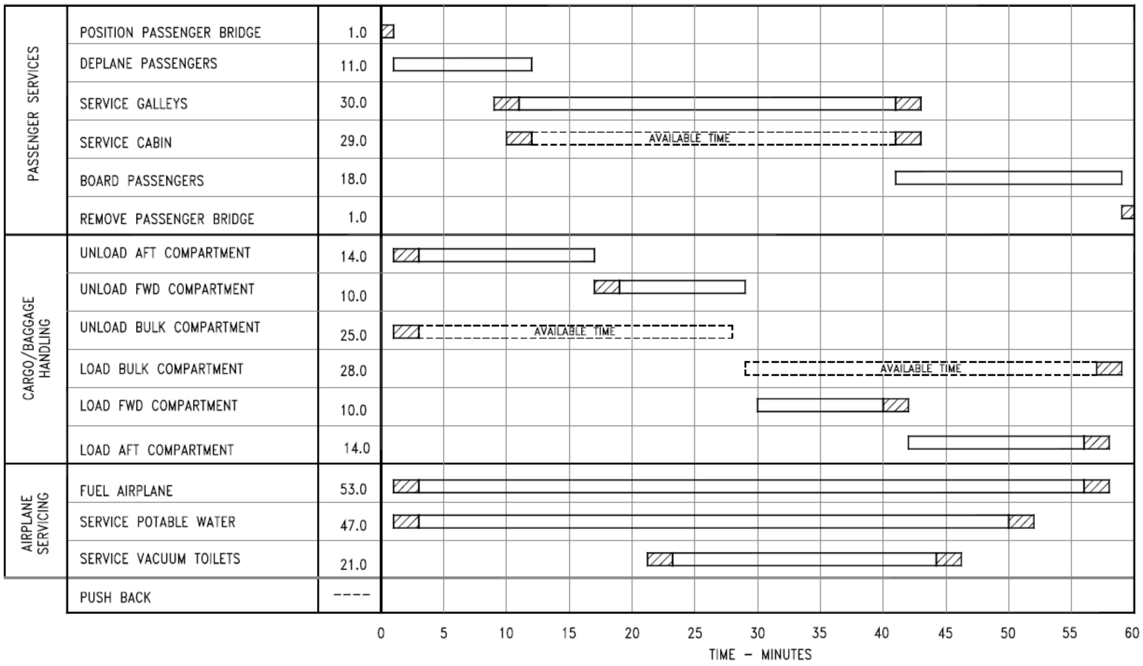


Figure 4-39 Turnaround Process of B747-400ER [73]

Figure 4-40 shows the turnaround process of B747-400, -400 Combi, and -400 Domestic. It assumes 442 passengers do de-boarding and boarding via one door. When it works the refueling process, it allows 43,300 gallons fuel loaded with 4,200 gallons reserve and uses four nozzles hydrant fueling at 35 PSIG. B747-400ER is designed for longer ranges, so it requires less fuel than 400ER. Regarding the supplying water process, it requires potable water 435 gallons at 30 GPM and 25 PSIG.

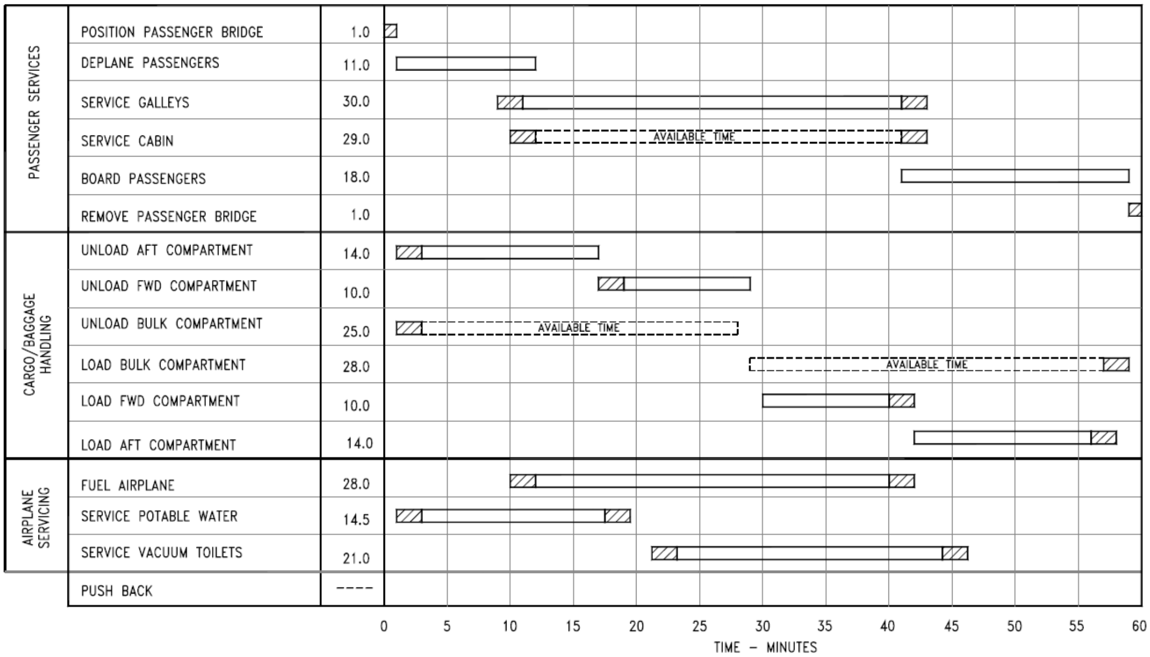


Figure 4-40 Turnaround Process of B747-400, -400 Combi, and -400 Domestic[73]

4.3.1.5 Summary of Boeing's Turnaround

The aircraft turnaround time process manufactured by Boeing has examined in section 4.3.1. There are a total of eleven types under four aircraft family for the turnaround time process: B737-600, B737-700, B737-800, B737-900, B777-200LR, B700-300ER, B787-8, B787-9, B787-10, B747-400ER, and B-747-400.

Boeing announced the activity time chart including position equipment, de-boarding/boarding, service galley, service cabin, loading/unloading, refueling, service potable water, and service vacuum toilets. The unusual activity is service cabin. Some aircraft can start any time after passengers' de-boarding, but it should be finished before the next flight's passenger boarding. Thus, some aircraft type has a time frame for that activity.

Table 4-11, 4-12, and 4-13 shows the summary of typical time for the turnaround process. Table 4-11 includes the aircraft that have short turnaround time, and table 4-12 includes the medium one. Lastly, table 4-13 includes the long one.

Table 4-11 Typical Time of Turnaround Process: Boeing 1 (Short)

Activity (min)	B737-600	B737-700	B737-800	B737-900
De-boarding	Start: 0 (1)+6	Start: 0 (1)+8	Start: 0 (1)+9	Start: 0 (1)+10
Boarding	Start: 17 9+(1)	Start: 19 12+(1)	Start: 21 14+(1)	Start: 22 15+(1)
Service galleys	Start:1 (2)+5+(3)+8+(2)	Start:1 (2)+6+(3)+9+(2)	Start:1 (2)+5+(3)+10+(2)	Start:1 (2)+5+(3)+10+(2)
Service cabin	Start: 4 (2)+10+(2)	Start: 7 (2)+10+(2)	Start: 8 (2)+11+(2)	Start: 9 (2)+11+(2)
Luggage/cargo unloading fwd	Start: 0 (2)+3	Start: 0 (2)+4	Start: 0 (2)+5	Start: 0 (2)+5
Luggage/cargo unloading aft	Start: 0 (2)+5	Start: 0 (2)+6	Start: 0 (2)+6	Start: 0 (2)+6
Luggage/cargo loading fwd	Start: 20 4+(2)	Start: 20 6+(2)	Start: 20 7+(2)	Start: 20 8+(2)
Luggage/cargo loading aft	Start: 7 7+(2)	Start: 8 8+(2)	Start: 8 9+(2)	Start: 8 10+(2)
Refueling	Start:6 (2)+9+(2)	Start:6 (2)+9+(2)	Start:6 (2)+9+(2)	Start:6 (2)+9+(2)
Vacuum toilets	Start: 8 (2)+10+(2)	Start: 8 (2)+10+(2)	Start: 8 (2)+10+(2)	Start: 8 (2)+10+(2)
Potable water	Start: 0 (2)+2+(2)	Start: 0 (2)+2+(2)	Start: 0 (2)+2+(2)	Start: 0 (2)+2+(2)
Total {pax}	29 min {108}	32 min {140}	36 min {160}	38 min {177}

The number in () means waiting time due to the resources' positioning or removal. In the chart by Boeing, there are two activities: Position passenger bridge and Remove passenger bridge. Those activities are considered in the de-boarding and boarding process as waiting time. Also, the number in [] means waiting time between positioning and activity start.

Table 4-12 Typical Time of Turnaround Process: Boeing 2 (Medium)

Activity (min)	B787-8	B777-200LR	B787-9	B777-300ER
De-boarding	Start: 0 (2)+6.9	Start: 0 (1)+7.5	Start: 0 (2)+9	Start: 0 (1)+9
Boarding	Start: 28.3 11.7+(1)	Start: 31 12.5+(1)	Start: 29 20+(1)	Start: 36 15+(1)
Service galleys 1	Start: 7 (2)+6+(1)	Start: 5.5 (2)+14.5+(3) +16+(2)	Start: 9 (2)+10+(1)	Start: 8 (2)+7.5+(3) +15+(2)
Service galleys 2	Start: 16 (2)+10.5+(1)	Start: 0 (2)+27+(2)	Start: 22 (2)+4+(1)	Start: 4 (2)+30+(2)
Service galleys 3	Start: 7 (2)+15+(1)	NaN	Start: 9 (2)+18+(1)	NaN
Service cabin	Available 8.9-28.3	Install: 3(2) Remove: 31.5(2) Available 5-31.5	Available 11-28	Install: 5(2) Remove: 36(2) Available 7-36
Luggage/cargo unloading fwd	Start: 0 (2)+16	Start: 0 (2)+[2]+18	Start: 0 (2)+20	Start: 0 (2)+24
Luggage/cargo unloading aft	Start: 0 (2)+12	Start: 0 (2)+14	Start: 0 (2)+16	Start: 0 (2)+20
Luggage/cargo loading fwd	Start: 18 16+(2)	Start: 29 14+(2)	Start: 22 20+(2)	Start: 28 20+(2)
Luggage/cargo loading aft	Start: 26 12+(2)	Start: 23 18+[2]+(2)	Start: 32 16+(2)	Start: 26 24+(2)
Refueling	Start: 0 (3)+35+(3)	Start:8 (2)+23+(2)	Start: 0 (3)+35+(3)	Start: 0 (2)+42+(2)
Waste water service	Start: 14 (2)+10+(2)	Start: 0 (2)+15+(2)	Start: 14 (2)+10+(2)	Start: 15 (2)+16.5+(2)
Vacuum toilets	Start: 0 (2)+10+(2)	Start: 0 (2)+17+(2)	Start: 0 (2)+10+(2)	Start: 0 (2)+11+(2)
Potable water	Service galleys 1 to 2, and Unloading to loading	NaN	Service galleys 1 to 2, and Unloading to loading	Na
Total {pax}	41 min {274}	45 min {375}	50 min {360}	52 min {451}

Table 4-13 Typical Time of Turnaround Process: Boeing 3 (Long)

Activity (min)	B787-10	B747-400ER	B747-400, -400 Combi, and -400 Domestic
De-boarding	Start: 0 (2)+10.3	Start: 0 (1)+11	Start: 0 (1)+11
Boarding	Start: 32.3 21.7+(1)	Start: 41 18+(1)	Start: 41 18+(1)
Service galleys 1	Start: 10.5 (2)+13+(1)	Start: 9 (2)+30+(2)	Start: 9 (2)+30+(2)
Service galleys 2	Start: 26.5 (2)+4+(1)	NaN	NaN
Service galleys 3	Start: 10.5 (2)+21+(1)	NaN	NaN
Service cabin	Available 12.3-32.3	Install: 10(2) Remove: 41(2) Available 12-41	Install: 10(2) Remove: 41(2) Available 12-41
Luggage/cargo unloading fwd	Start: 0 (2)+22	Start: 17 (2)+10	Start: 17 (2)+10
Luggage/cargo unloading aft	Start: 0 (2)+18	Start: 1 (2)+14	Start: 1 (2)+14
Luggage/cargo loading fwd	Start: 24 22+(2)	Start: 30 10+(2)	Start: 30 10+(2)
Luggage/cargo loading aft	Start: 36 18+(2)	Start: 42 14+(2)	Start: 42 14+(2)
Refueling	Start: 0 (3)+35+(3)	Start: 1 (2)+53+(2)	Start: 10 (2)+28+(2)
Vacuum toilets	Start: 14 (2)+10+(2)	Start: 21 (2)+21+(2)	Start: 21 (2)+21+(2)
Potable water	Start: 0 (2)+10+(2)	Start: 1 (2)+47+(2)	Start: 1 (2)+14.5+(2)
Critical Path	Service galleys 1 to 2, and Unloading to loading	NaN	NaN
Total {pax}	56 min {411}	60 min {442}	60 min {442}

The critical path should be focused in order to simulation modeling. The B787 family only has a critical path. Regarding the catering activity, there are two galley trucks. However, B787 requires three galley services through forward (catering 1), mid (catering 2), and aft (catering 3). Thus, catering 1 and catering 2 should be done sequentially by one truck and catering 3 should be done by another truck. There is another critical path for B787 regarding baggage/cargo handling: unloading should be done before loading activity.

4.3.2 Airbus

Table 4-8 shows the top 9 aircraft sorted by the number of the net orders by historical records. The popular aircraft were shown in table 4-8 sorted by the number of the net orders. There are two manufacturers on the list: Boeing and Airbus. Boeing's aircraft were examined in section 4.3.1. Thus, in this section, the aircraft manufactured by Airbus will be focused: Airbus 320, Airbus 330, Airbus 350, and Airbus 380. The turnaround information in the manufacturer's manual will be introduced and explained.

4.3.2.1 Airbus 320 Family

Airbus 320 family is first ranked aircraft when sorting the number of the net orders by historical records. Based on the Airbus' announcement, it is the best-selling single-aisle aircraft worldwide [74]. The two aircraft will be examined here: A320-200 and A320NEO(New Engine Option). The NEO can save a minimum of 15 % fuel and trip an additional 500 nm flight range [74].

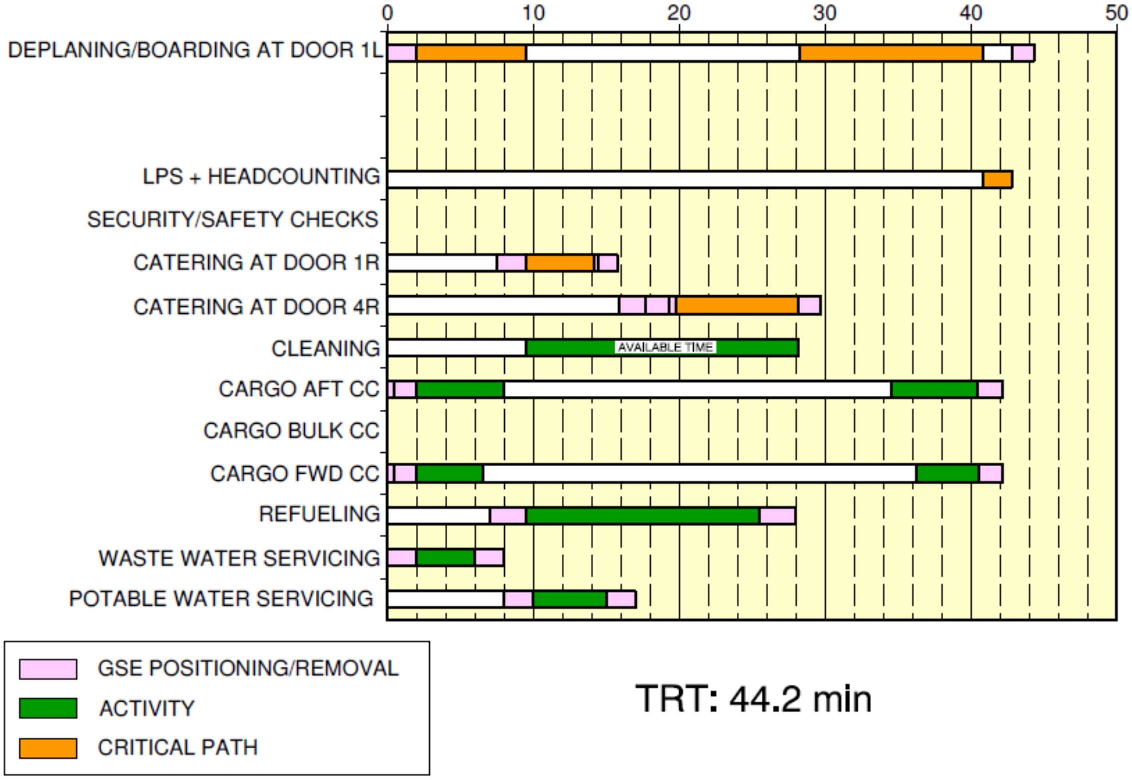


Figure 4-41 Turnaround Process of A320 family [74]

Figure 4-41 shows the turnaround process of A320 family: A320-200 and A320 NEO. The required time is 44.2 minutes for the typical time for ramp activities during aircraft turnaround process. However, the typical time is calculated based on the several work assumptions so that the actual time may not identical to the typical time because of each operator’s specific practices, resources, equipment, and operating conditions [74].

The followings represent the assumptions to derive the turnaround time chart in figure 4-41. There are a total of 150 passengers (12 first class and 138 economy class) that do de-boarding and boarding through one passenger boarding bridge used at one door. Also, there are no passengers with reduced mobility on board. Regarding passenger loading rates, the de-boarding rate for passengers is 20 per minute, and the boarding rate for passengers is 12 per minute. Here are the additional time assignments regarding passenger handling:

- Equipment positioning + opening door = +2 minute
- Closing door + equipment removal = +1.5 minute
- Last Passenger Seating allowance (LPS) + Head counting = +2 minute

It assumes that 100% passenger and cargo exchange. There are two cargo loaders and one belt loader for A320 family. Forward cargo compartment has three containers, and aft cargo compartment has four containers. The container unloading/loading time is 1.5 minute per container. Here are the additional time assignments regarding baggage/cargo handling:

- Opening door + equipment positioning = +2 minute
- Equipment removal + closing door = +1.5 minute

Refueling should proceed when the passengers are not on board. When it works the refueling process, it allows uplifted quantity as 5,283 gallons at 50 PSIG and uses one hose through the right wing. Here is the additional time assignment regarding refueling:

- Truck positioning/removal + connection/disconnection times = +2.5 minute

There is one catering truck for galley service. It operates sequentially at doors 1R and 4R. There are also eleven Full-size trolley equivalents (FSTE) to unload and load: four FSTE at door 1R and seven FSTE at door 4R. Here are the additional time assignments regarding catering:

- Equipment positioning + opening door = +2 minute
- Closing door + equipment removal = +1.5 minute
- Time to drive from one door to the other = +2 minute
- Time for trolley exchange = +1.2 minute per FSTE

Regarding the general servicing or other turnaround activity, cleaning is performed in the available time frame. Air conditioning uses one hose, and toilet servicing includes draining and rinsing. Supplying water allows 100% uplift such as 53 gallons, and supplying power unit allows up to 90kVA.

4.3.2.2 Airbus 330 Family

According to Airbus, there are more than 100 operators of A330 family flying to some 400 airports [75]. It means that A330 family is widely used and popular wide-bodies in the world. In this section, A330-200 and A330-300 will be examined. Those has various payload capabilities: ranging from 200 passengers in a high comfort multi-class layout up to 440 passengers in a high-efficiency configuration [75].

Additionally, the latest derivative of the A330 family will be examined: A330-800 and A330-900. Those can offer the reduced fuel consumption about 14 percent per seat. A330-800 share the same fuselage length of A330-200. Likewise, A330-900 share the one of A330-300. [75]

Figure 4-42 shows the turnaround process of the A330 family: A330-300 and A330-900. The required time is 59 minutes for the ordinary time for the activities during the turnaround process. The followings represent the assumptions to derive the turnaround time chart in figure 4-42.

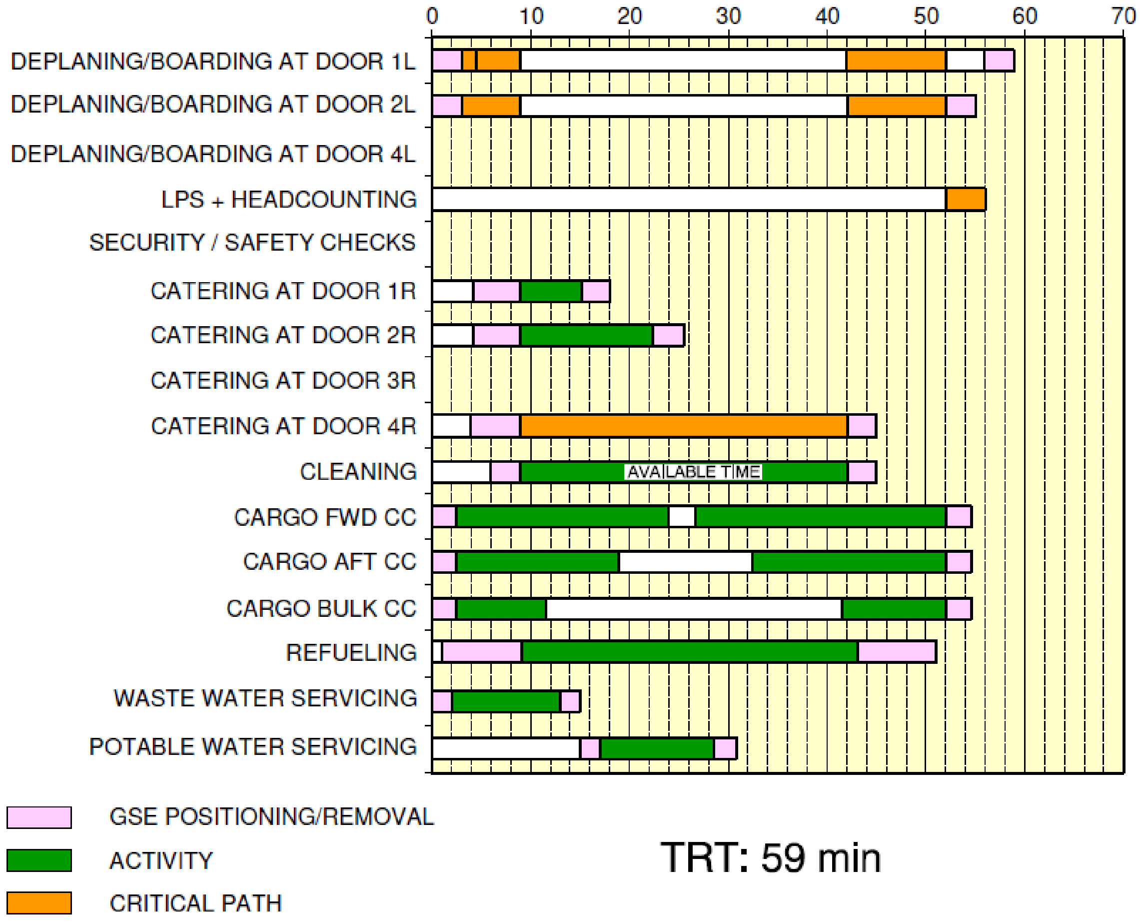


Figure 4-42 Turnaround Process of A330-300 and A330-900 [75]

There are a total of 300 passengers (36 business class and 264 economy class) that do de-boarding and boarding through two passenger boarding bridges used at two doors. Also, there are no passengers with reduced mobility on board. In terms of passenger loading rates, the de-boarding rate for passengers is 25 per minute per door, and the boarding rate for passengers is 15 per minute per door. There are 150 passengers at each door. Here are the additional time assignments regarding passenger handling:

- Equipment positioning + opening door = +3 minute
- Closing door + equipment removal = +3 minute

- LPS + Head counting = +4 minute

It assumes that 100% passenger and cargo exchange. There are two cargo loaders and one belt loader for A330-300, and -900. Forward cargo compartment has 18 containers, and aft cargo compartment has 14 containers. The container unloading time is 1.2 minute per container and the loading time is 1.4 minute per container. Here are the additional time assignments regarding baggage/cargo handling:

- Opening door + equipment positioning = +2.5 minute
- Equipment removal + closing door = +2.5 minute

Refueling can proceed when the passengers are on board. When it works the refueling process, it allows the final fuel on board as 23,775 gallons at 50 PSIG and uses two hoses. Here is the additional time assignment regarding refueling:

- Hydrant positioning + connection = +8 minutes
- Disconnection + hydrant removal = +8 minutes

There are three catering trucks for galley service. It operates simultaneously at doors 1R, 2R and 4R. There are also 35 FSTE to unload and load: 4 FSTE at door 1R, 9 FSTE at door 2R and 22 FSTE at door 4R. Here are the additional time assignments regarding catering:

- Equipment positioning + opening door = +5 minute
- Closing door + equipment removal = +3 minute
- Time for trolley exchange = +1.5 minute per FSTE

Regarding the general servicing or other turnaround activity, cleaning is performed in the available time frame as well. Air conditioning uses up to two hoses, and waste water servicing includes draining and rinsing. Supplying water allows 100% uplift such as 185 gallons, and supplying power unit allows up to 2∗90kVA.

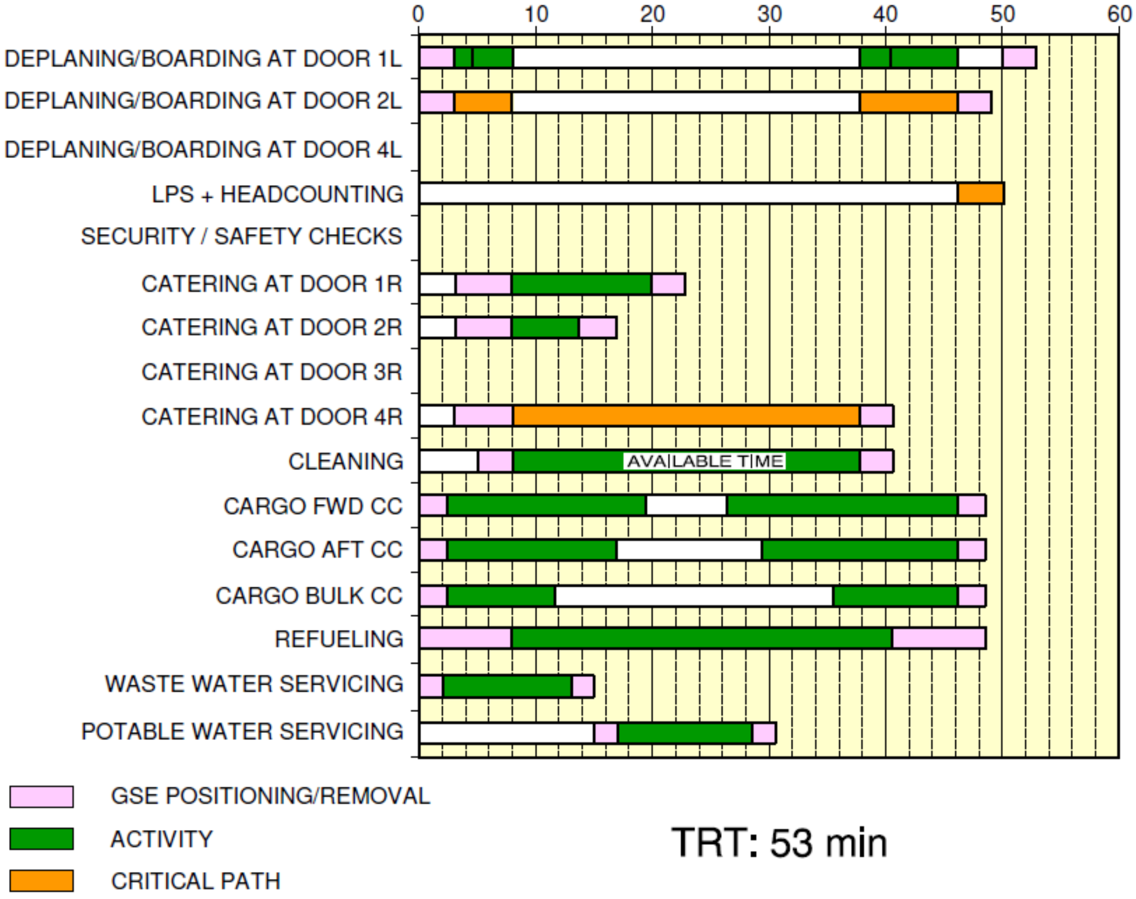


Figure 4-43 Turnaround Process of A330-200 and A330-800 [75]

Figure 4-43 shows the turnaround process of the A330 family: A330-200 and A330-800. The required time is 53 minutes for the typical time for ramp activities during aircraft turnaround process.

There are a total of 246 passengers (36 business class and 210 economy class) that do de-boarding and boarding through two passenger boarding bridges used at two doors. Also, there are no passengers with reduced mobility on board. In terms of passenger loading rates, the de-boarding rate for passengers is 25 per minute per door, and the boarding rate for passengers is 15 per minute per door. There are 123 passengers at each door. Here are the additional time assignments regarding passenger handling:

- Equipment positioning + opening door = +3 minute
- Closing door + equipment removal = +3 minute
- LPS + Head counting = +4 minute

It assumes that 100% passenger and cargo exchange. There are two cargo loaders and one belt loader for A330-200, and -800. Forward cargo compartment has 14 containers, and aft cargo compartment has 12 containers. The container unloading time is 1.2 minute per container and the loading time is 1.4 minute per container. Here are the additional time assignments regarding baggage/cargo handling:

- Opening door + equipment positioning = +2.5 minute
- Equipment removal + closing door = +2.5 minute

Refueling can proceed when the passengers are on board. When it works the refueling process, it allows the final fuel on board as 30,380 gallons at 50 PSIG and uses four hoses. Here is the additional time assignment regarding refueling:

- Hydrant positioning + connection = +8 minutes
- Disconnection + hydrant removal = +8 minutes

There are three catering trucks for galley service. It operates simultaneously at doors 1R, 2R and 4R. There are also 32 FSTE to unload and load: 8 FSTE at door 1R, 4 FSTE at door 2R and 20 FSTE at door 4R. Here are the additional time assignments regarding catering:

- Equipment positioning + opening door = +5 minute
- Closing door + equipment removal = +3 minute
- Time for trolley exchange = +1.5 minute per FSTE

Regarding the general servicing or other turnaround activity, cleaning is performed in the available time frame as well. Air conditioning uses up to two hoses, and waste water servicing includes draining and rinsing. Supplying water allows 100% uplift such as 185 gallons, and supplying power unit allows up to $2*90$kVA.

4.3.2.3 Airbus 350 Family

The A350 family is wide-body airplane to operate as long-haul airliners. It includes two aircraft: A350-900 and A350-1000. The A350-900 is smaller than A350-1000. The A350-1000 is Airbus largest Wide Body aircraft in the twin-aisle category with a 7-meter-longer fuselage, which contains 40 more seats and a 40-per-cent-larger space for premium cabin products than the A350-900 [76].

The A350 family gives a high level of cargo hold capability and flexibility to meet the requirements of the market: Two wide cargo doors and a cargo loading system, compatible with most lower deck cargo containers and pallet standards, allow interlining operations and facilitate the loading [76].

Figure 4-44 shows the turnaround process of A350-900. The required time is 61 minutes for the representative time for ground activities during the turnaround process.

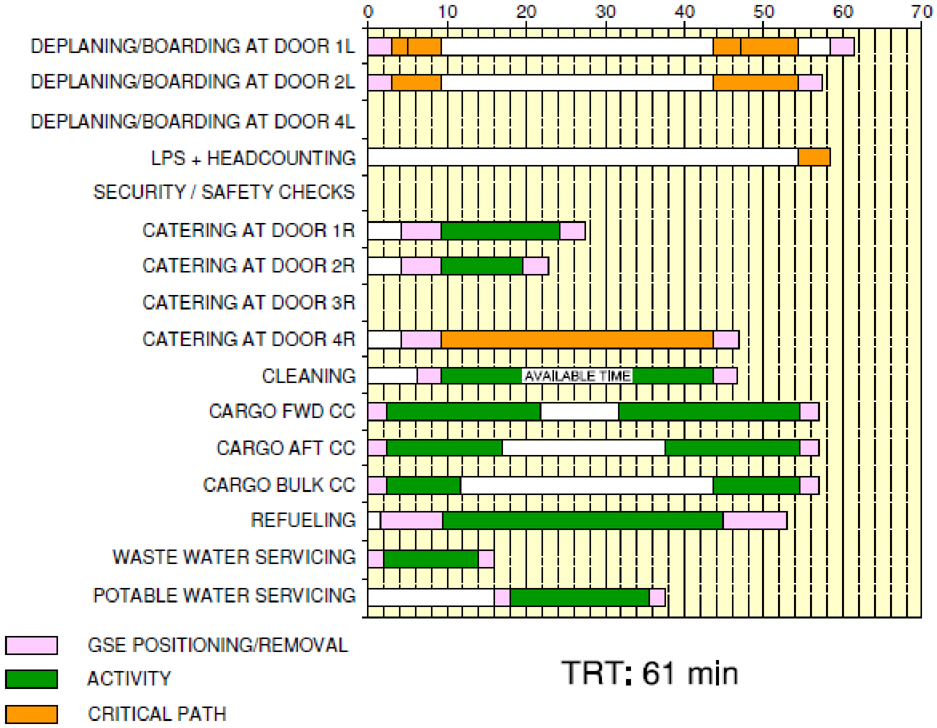


Figure 4-44 Turnaround Process of A350-900 [76]

There are a total of 315 passengers (48 business class and 267 economy class) that do de-boarding and boarding through two passenger boarding bridges used at two doors (1L and 2L). Also, there are no passengers with reduced mobility on board. In terms of passenger loading rates, the de-boarding rate for passengers is 25 per minute per door, and the boarding rate for passengers is 15 per minute per door. There are 158 passengers at door 1L, and 157 passengers at door 2L. Here are the additional time assignments regarding passenger handling:

- Equipment positioning + opening door = +3 minute

- Closing door + equipment removal = +3 minute
- LPS + Head counting = +4 minute

It assumes that 100% passenger and cargo exchange. There are two cargo loaders and one belt loader for A350-900. Forward cargo compartment has eight containers and four pallets, and aft cargo compartment has four containers and four pallets. The container unloading time is 1.2 minute per container and the loading time is 1.4 minute per container. The pallet unloading time is 2.4 minute per pallet and the loading time is 2.8 minute per pallet. Here are the additional time assignments regarding baggage/cargo handling:

- Opening door + equipment positioning = +2.5 minute
- Equipment removal + closing door = +2.5 minute

Refueling can proceed when the passengers are on board. When it works the refueling process, it allows the final fuel on board as 26,418 gallons at 40 PSIG and uses two hoses. The important guideline is refueling from one side of the aircraft at a time in order to prevent damage to the aircraft fuel system. Here is the additional time assignment regarding refueling:

- Hydrant positioning + connection = +8 minutes
- Disconnection + hydrant removal = +8 minutes

There are three catering trucks for galley service. It operates simultaneously at doors 1R, 2R and 4R. There are also 40 FSTE to unload and load: 10 FSTE at door 1R, 7 FSTE at door 2R and 23 FSTE at door 4R. Here are the additional time assignments regarding catering:

- Equipment positioning + opening door = +5 minute
- Closing door + equipment removal = +3 minute
- Time for trolley exchange = +1.5 minute per FSTE

Regarding the general servicing or other turnaround activity, cleaning is performed in the available time frame as well. Air conditioning uses up to two hoses, and waste water servicing includes draining and rinsing. Supplying water allows 100% uplift such as 280 gallons, and supplying power unit allows up to 2∗90kVA.

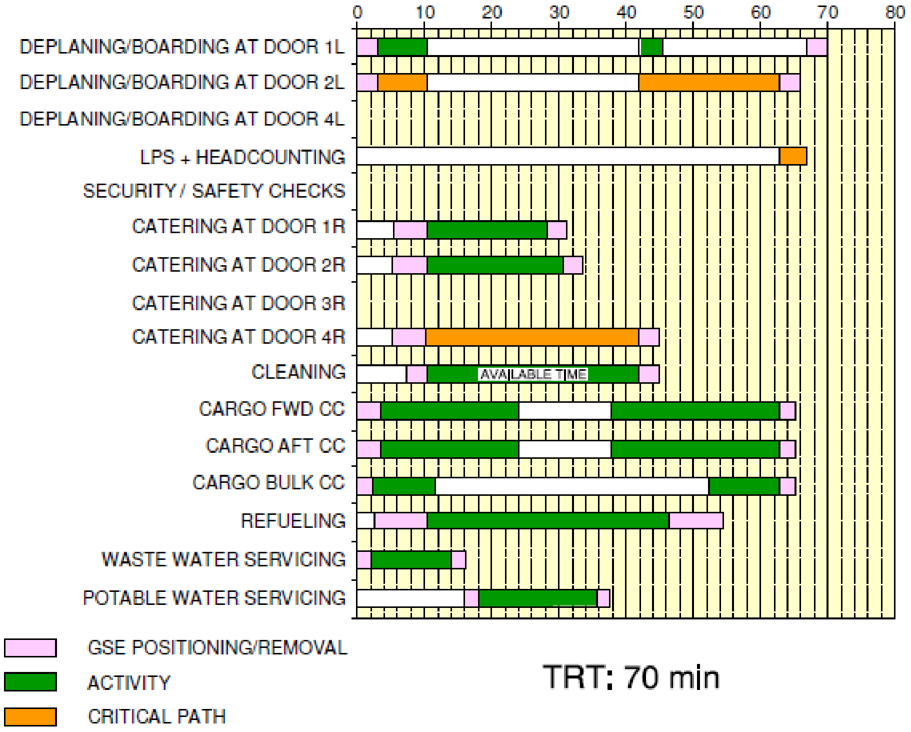


Figure 4-45 Turnaround Process of A350-1000 [76]

Figure 4-45 shows the turnaround process of A350-1000. The required time is 70 minutes for the standard time for ground activities during the turnaround process. The followings show the assumption for A350-1000 turnaround process time.

There are a total of 369 passengers (54 business class and 315 economy class) that do de-boarding and boarding through two passenger boarding bridges used at two doors (1L and 2L). Also, there are no passengers with reduced mobility on board.

In terms of passenger loading rates, the de-boarding rate for passengers is 25 per minute per door, and the boarding rate for passengers is 15 per minute per door. In the de-boarding process, there are 184 passengers at door 1L, and 185 passengers at door 2L in de-boarding process.

Also, in the boarding process, there are 54 passengers at door 1L, and 315 passengers at door 2L in de-boarding process. Here are the additional time assignments regarding passenger handling:

- Equipment positioning + opening door = +3 minute
- Closing door + equipment removal = +3 minute
- LPS + Head counting = +4 minute

It assumes that 100% passenger and cargo exchange. There are two cargo loaders and one belt loader for A350-1000. Forward cargo compartment has six containers and six pallets, and aft cargo compartment has fourteen containers and two pallets. The container unloading time is 1.2 minute per container and the loading time is 1.4 minute per container.

The pallet unloading time is 2.4 minute per pallet and the loading time is 2.8 minute per pallet. Here are the additional time assignments regarding baggage/cargo handling:

- Opening door + equipment positioning = +2.5 minute
- Equipment removal + closing door = +2.5 minute

Refueling can proceed when the passengers are on board. When it works refueling process, it allows the final fuel on board as 26,418 gallons at 40 PSIG and uses two hoses. The important guideline is refueling from one side of the aircraft at a time, because of protecting the aircraft fuel system. Here is the additional time assignment regarding refueling:

- Hydrant positioning + connection = +8 minutes
- Disconnection + hydrant removal = +8 minutes

There are three catering trucks for galley service. It operates simultaneously at doors 1R, 2R and 4R. There are also 45 FSTE to unload and load: 12 FSTE at door 1R, 8 FSTE at door 2R, 21 FSTE at door 4R and 4 FSTE at door 3R as stowage area. Here are the additional time assignments regarding catering:

- Equipment positioning + opening door = +5 minute
- Closing door + equipment removal = +3 minute
- Time for trolley exchange = +1.5 minute per FSTE

Regarding the general servicing or other turnaround activity, cleaning is performed in the available time frame as well. Air conditioning uses up to two hoses, and waste water servicing includes draining and rinsing. Supplying water allows 100% uplift such as 280 gallons, and supplying power unit allows up to 2∗90kVA.

4.3.2.4 Airbus 380 Family

A baseline passenger aircraft is A380-800 for the generation of A380 family. The A380-800 is designed for very long range flights. There are various payload capabilities: ranging from 400 passengers in a very comfortable multiclass configuration, up to 853 passengers in an all-economy class configuration [77].

Two types of turnaround process will be examined: using both the main deck and upper deck and using the main deck only.

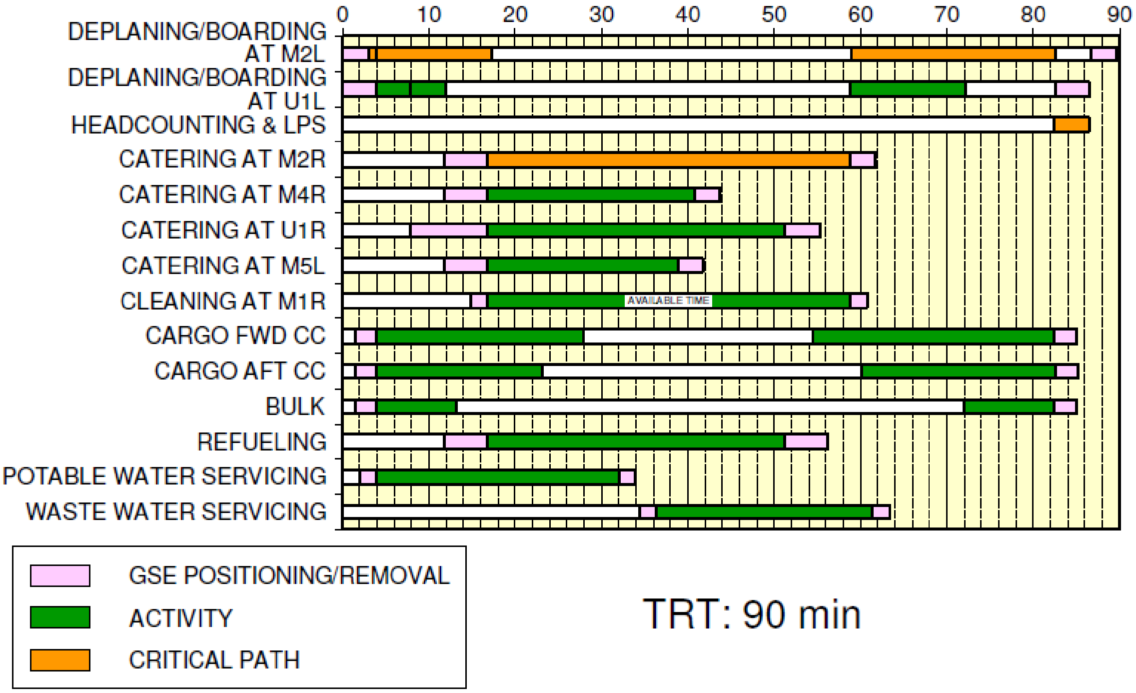


Figure 4-46 Turnaround Process of A380 (Main and Upper Deck) [77]

Figure 4-46 shows the turnaround process of A380-800 when standard servicing via the main deck and upper deck. The required time is 90 minutes for the standard time for ground activities during the turnaround process. The followings show the assumption for A380-800 turnaround process time via the main deck and upper deck.

There are a total of 555 passengers (22 first class, 96 business class, and 437 economy class) that do de-boarding and boarding through two passenger boarding bridges at two doors (M2L and U1L). Also, there are no passengers with reduced mobility on board.

In terms of passenger loading rates, the de-boarding rate for passengers is 25 per minute per door, and the boarding rate for passengers is 15 per minute per door. There are 356 passengers at the door M2L and 199 passengers at the door U1L for de-boarding and boarding process. Here are the additional time assignments regarding passenger handling:

- Equipment positioning main deck + opening door = +3 minute
- Closing door + equipment removal main deck = +3 minute
- Equipment positioning upper deck + opening door = +4 minute
- Closing door + equipment removal upper deck = +4 minute
- LPS + Head counting = +4 minute

It assumes that 100% passenger and cargo exchange. There are two cargo loaders and one belt loader for A380-800. Forward cargo compartment has 20 containers, and aft cargo compartment has 16 containers. The container unloading time is 1.2 minute per container and the loading time is 1.4 minute per container. Here are the additional time assignments regarding baggage/cargo handling:

- Opening door + equipment positioning = +2.5 minute
- Equipment removal + closing door = +2.5 minute

When it works the refueling process, it allows 64,115 gallons at 40 PSIG. Here is the additional time assignment regarding refueling:

- Dispenser positioning + connection = +5 minutes
- Disconnection + dispenser removal = +5 minutes

There are three main deck catering trucks and one upper deck catering trucks for galley service. There are 78 FSTE to unload and load: 28 FSTE at the door M2R, 16 FSTE at the door M4R, 23 FSTE at the door U1R, and 11 FSTE at the door M5L. Here are the additional time assignments regarding catering:

- Equipment positioning main deck + opening door = +5 minute
- Closing door + equipment removal main deck = +3 minute
- Equipment positioning upper deck + opening door = +9 minute
- Closing door + equipment removal upper deck = +4 minute
- Time for trolley exchange = +1.5 minute per FSTE
- Time for trolley exchange via lift = +2 minute per FSTE

Regarding the general servicing or other turnaround activity, cleaning is performed in the available time frame as well. Air conditioning uses up to four hoses, and waste water servicing includes draining and rinsing. Supplying water allows 100% uplift such as 449 gallons, and supplying power unit allows up to 4∗90kVA.

Figure 4-47 shows the turnaround process of A380-800 when servicing via the main deck. The required time is 140 minutes for the representative time for ground activities during the turnaround process. The followings show the assumption for A380-800's turnaround process time when using the main deck only.

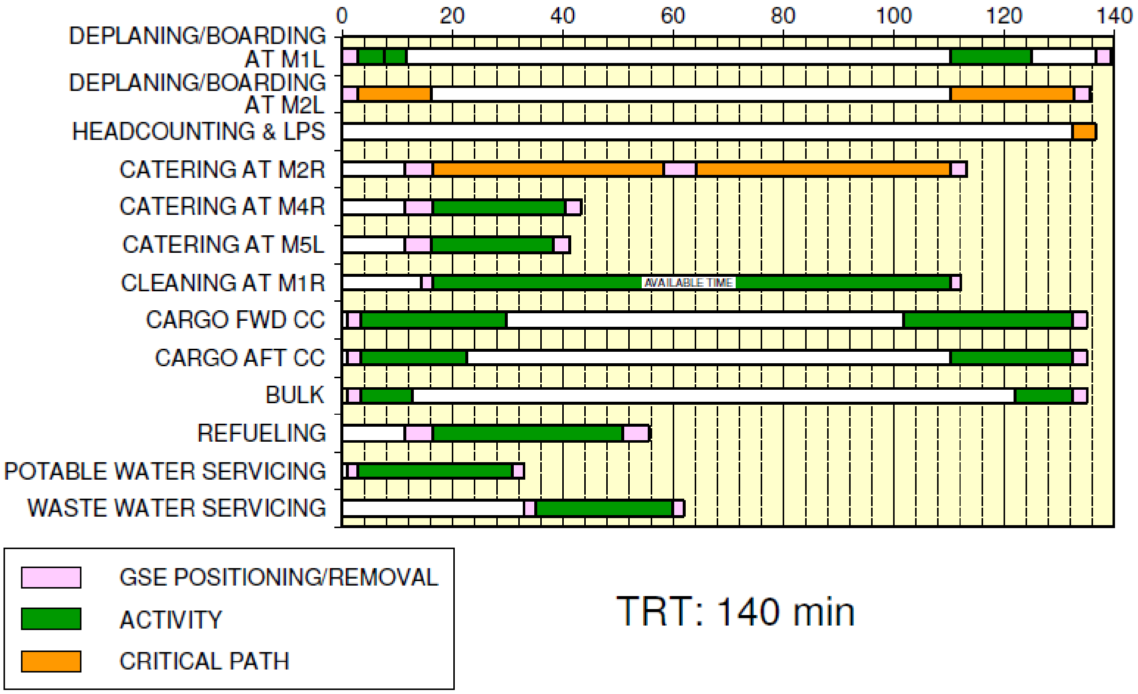


Figure 4-47 Turnaround Process of A380 (Main Deck) [77]

There are a total of 555 passengers (22 first class, 96 business class, and 437 economy class) that do de-boarding and boarding through two passenger boarding bridges used at two doors (M1L and M2L). Also, there are no passengers with reduced mobility on board. In terms of passenger loading rates, the de-boarding rate for passengers is 25 per minute per door, and the boarding rate for passengers is 15 per minute per door. There are 221 passengers at the door M1L and 334 passengers at the door M2L. Here are the additional time assignments regarding passenger handling:

- Equipment positioning + opening door = +3 minute
- Closing door + equipment removal = +3 minute
- LPS + Head counting = +4 minute

It assumes that 100% passenger and cargo exchange. There are two cargo loaders and one belt loader for A380-800. Forward cargo compartment has 20 containers, and aft cargo compartment has 16 containers. The container unloading time is 1.2 minute per container and the loading time is 1.4 minute per container. Here are the additional time assignments regarding baggage/cargo handling:

- Opening door + equipment positioning = +2.5 minute
- Equipment removal + closing door = +2.5 minute

When it works the refueling process, it allows 64,115 gallons at 40 PSIG. Here is the additional time assignment regarding refueling:

- Dispenser positioning + connection = +5 minutes
- Disconnection + dispenser removal = +5 minutes

There are three main deck catering trucks for galley service. There are 78 FSTE to unload and load: 28 FSTE at door M2R, 16 FSTE at door M4R, 23 FSTE at the door U1R and 11 FSTE at door M5L. Here are the additional time assignments regarding catering:

- Equipment positioning + opening door = +5 minute
- Closing door + equipment removal = +3 minute
- Time for trolley exchange = +1.5 minute per FSTE
- Time for trolley exchange via lift = +2 minute per FSTE

Regarding the general servicing or other turnaround activity, cleaning is performed in the available time frame as well. Air conditioning uses up to four hoses, and waste water servicing includes draining and rinsing. Supplying water allows 100% uplift such as 449 gallons, and supplying power unit allows up to 4∗90kVA.

4.3.2.5 Summary of Airbus' Turnaround

The aircraft turnaround time process manufactured by Airbus has examined in section 4.3.2. There are total seven types of turnaround process: A320, A330-300/900, A330-200/800, A350-900, A350-1000, A380-800 (main deck only) and A380-800 (main deck and upper deck).

Airbus announced the activity time chart including de-boarding, boarding, catering, cleaning, loading, unloading, refueling, supplying water, and waste water servicing. The cleaning activity is still noteworthy. Airbus assumes that cleaning can proceed when passengers' de-boarding ends. It means cleaning can start any time after passengers' de-boarding, but it should be finished before the next flight's passenger boarding. Thus, there is the only available time frame for cleaning activity.

The remarkable point of turnaround time chart is the critical path. Each aircraft has a critical path for the turnaround process: de-boarding and catering, catering-boarding, and LPS (+head-counting)-door removal. Simulation modeling should obey these paths.

Table 4-14 and 4-15 show the summary of typical time for the turnaround process. Table 4-14 includes the aircraft that has shorter turnaround time, and table 4-15 includes the aircraft that has longer turnaround time.

Table 4-14 Typical Time of Turnaround Process: Airbus 1

Activity (min)	A320-200, NEO	A330-200,800	A330-300,900	A350-900
De-boarding1	Start: 0 (2)+7.5	Start: 0 (3)+5	Start: 0 (3)+6	Start: 0 (3)+6.3
Boarding1	Start: 28 12.7+(LPS)+(1.5)	Start: 37.8 8.2+(LPS)+(3)	Start: 42 10+(LPS)+(3)	Start: 43.5 10.5+(LPS)+(3)
De-boading2	NaN	Start: 0 (3)+5	Start: 0 (3)+6	Start: 0 (3)+6.3
Boarding2	NaN	Start: 37.8 8.2+(3)	Start: 42 10+(3)	Start: 43.5 10.5+(3)
LPS (including headcounting)	Start: 40.7 2	Start: 46 4	Start: 52 4	Start: 53 4
Catering 1	Start:7.5 (2)+4.7+(1.5)	Start:3 (5)+12+(3)	Start:4 (5)+6+(3)	Start: 4.3 (5)+15+(3)
Catering 2	Start:16 (2)+(2)+8+(1.5)	Start:3 (5)+5.8+(3)	Start:4 (5)+13+(3)	Start: 4.3 (5)+10.5+(3)
Catering 3	NaN	NaN	NaN	NaN
Catering 4	NaN	Start:3 (5)+29.8+(3)	Start:4 (5)+33+(3)	Start: 4.3 (5)+34.2+(3)
Cleaning	Available 9.5-28	Install: 5(3) Remove: 37.8(3) Available 8-37.8	Install: 6(3) Remove: 42(3) Available 9-42	Install: 6.3(3) Remove: 43.5(3) Available 9.3-43.5
Luggage/cargo unloading fwd	Start: 0 (2)+4.5	Start: 0 (2.5)+17	Start: 0 (2.5)+21.5	Start: 0 (2.5)+19.5
Luggage/cargo unloading aft	Start: 0 (2)+6	Start: 0 (2.5)+14.5	Start: 0 (2.5)+16.5	Start: 0 (2.5)+14.5
Luggage/cargo loading fwd	Start: 36 4.5+(1.5)	Start: 26.2 19.8+(2.5)	Start: 26.5 25.5+(2.5)	Start: 32 22.5+(2.5)
Luggage/cargo loading aft	Start: 34.5 6+(1.5)	Start: 29.5 16.5+(2.5)	Start: 32.5 19.5+(2.5)	Start: 37.5 17+(2.5)
Refueling	Start:7 (2.5)+16+(2.5)	Start: 0 (8)+32.5+(8)	Start: 1 (8)+34+(8)	Start: 1.5 (8)+35+(8)
Waste water service	Start: 0 (2)+4+(2)	Start: 0 (2)+11+(2)	Start: 0 (2)+11+(2)	Start: 0 (2)+12+(2)
Potable water service	Start:8 (2)+5+(2)	Start:15 (2)+11.5+(2)	Start:15 (2)+11.5+(2.5)	Start: 16 (2)+17.8+(2)
Critical path	Deboarding-catering1&4-boarding-LPS	Deboarding-catering4-boarding-LPS	Deboarding-catering4-boarding-LPS	Deboarding-catering4-boarding-LPS
Total {pax}	44.2 {150}	53 {246}	59 {300}	61 {315}

Table 4-15 Typical Time of Turnaround Process: Airbus 2

Activity (min)	A350-1000	A380 Main and upper deck	A380-Main deck
De-boarding1	Start: 0 (3)+7.4	Start: 0 (3)+14.2	Start: 0 (3)+8.9
Boarding1	Start: 42 3.6+[21.4]+(3)	Start: 59.3 23.7+(LPS)+(3)	Start: 110.7 14.7+[11.6]+(3)
De-boading2	Start: 0 (3)+7.4	Start: 0 (4)+8	Start: 0 (3)+13.4
Boarding2	Start: 42 21+(LPS)+(3)	Start: 59.3 13.3+[10.4]+(4)	Start: 110.7 22.3+(LPS)+(3)
LPS (including headcounting)	Start: 63 4	Start: 83 4	Start: 133 4
Catering 1	Start: 5.4 (5)+17.6+(3)	Start: 12 (5)+42.3+(3)	Start: 12 (5)+42+(5.5)+46+(3)
Catering 2	Start: 5.4 (5)+19.4+(3)	Start: 12 (5)+24+(3)	Start: 12 (5)+24+(3)
Catering 3	NaN	Start: 8 (9)+34.5+(4)	NaN
Catering 4	Start: 5.4 (5)+31.6+(3)	Start: 12 (5)+22+(3)	Start: 12 (5)+22+(3)
Cleaning	Install: 7.4(3) Remove: 42(3) Available 10.4-42	Install: 15.2(2) Remove: 59.3(2) Available 17.2-59.3	Install: 14(2) Remove: 110(2) Available 16-110
Luggage/cargo unloading fwd	Start: 0 (2.5)+20.5	Start: 1.5 (2.5)+24	Start: 1.5 (2.5)+28
Luggage/cargo unloading aft	Start: 0 (2.5)+20.5	Start: 1.5 (2.5)+19	Start: 1.5 (2.5)+18
Luggage/cargo loading fwd	Start: 38 24.5+(2.5)	Start: 54 28.5+(2.5)	Start: 102 30+(2.5)
Luggage/cargo loading aft	Start: 38 24.5+(2.5)	Start: 60 22.5+(2.5)	Start: 110 22+(2.5)
Refueling	Start: 2.5 (8)+36+(8)	Start: 12 (5)+34+(5)	Start: 12 (5)+34+(5)
Waste water service	Start: 0 (2)+12+(2)	Start: 2 (2)+28+(2)	Start: 1 (2)+28+(2)
Potable water service	Start: 16 (2)+17.8+(2)	Start: 34 (2)+25.5+(2)	Start: 33 (2)+25+(2)
Critical path	Deboarding-catering4-boarding-LPS	Deboarding-catering1-boarding-LPS	Deboarding-catering1-boarding-LPS
Total {pax}	70 {369}	90 {555}	140 {555}

Each activity’s start time is defined in the table. The number in () means waiting time due to the resources’ positioning or removal. Also, the number in [] means waiting time between boarding time and door removal. Some door assigned fewer passengers than the other door. Thus it requires waiting for the end of the other door’s boarding. The last row shows the total time and total assigned passengers.

4.3.3 Standard Format of Turnaround Process

In section 4.3.1 and 4.3.2, the turnaround time chart of popular aircraft was discussed. Section 4.3.1 shows the Boeing’s aircraft, and section 4.3.2 shows the Airbus’ aircraft. The whole frame is almost similar, but it can notice the differences between the two manufacturers. This section shows how to define the standard format of turnaround time process.

4.3.3.1 Turnaround Activity

Table 4-16 shows the activity summary of two manufacturers. The first difference results from the number of the turnaround activities. Airbus has one more activity than Boeing: LPS activity. Thus, for the aircraft model by Airbus, LPS activity is removed, and the boarding process will get LPS time.

Table 4-16 Activity Summary

Activity by Airbus	Activity by Boeing
De-boarding	De-boarding
Boarding	Boarding
LPS (including headcounting)	Service galleys
Catering	Service cabin
Cleaning	Luggage/cargo unloading fwd
Luggage/cargo unloading fwd	Luggage/cargo unloading aft
Luggage/cargo unloading aft	Luggage/cargo loading fwd
Luggage/cargo loading fwd	Luggage/cargo loading aft
Luggage/cargo loading aft	Refueling
Refueling	Vacuum toilets service
Waste water service	Potable water service
Potable water service	

The second difference results from the name of the activities. When looking at the table 4-16, the activity name by Airbus is simpler than Boeing. Thus, the name of the activity by Boeing will be replaced. Additionally, potable water service will be replaced as supplying water, and luggage/cargo processes will be called merely, i.e., unloading-fwd, or loading-fwd.

Table 4-17 shows the standard format of turnaround activity. This format will be applied to the simulation modeling.

Table 4-17 Standard Format of Turnaround Activity

Activity
De-boarding
Boarding
Catering
Cleaning
Unloading-fwd
Unloading-aft
Loading-fwd
Loading-aft
Refueling
Waste water
Supplying water

4.3.3.2 Turnaround Time

Table 4-18 shows the numerical features of aircraft turnaround time. There are a total of aircraft 18 models. In general, the turnaround time announced by Boeing is shorter than the Airbus one. For example, B737-800 has more passengers than A320. However, it takes less time even though de-boarding and boarding speed is slow. One of the possible reason is LPS time of Airbus. In order to identify other possible reasons, the categories included will be considered in more detail.

Table 4-18 Numerical Features of Aircraft Turnaround Time

Aircraft	Turnaround Time (min)	Number of Passengers	De-Boarding /Boarding Speed	Boarding bridge	Catering truck
B737-600	29	108	18/12	1	1
B737-700	32	140	18/12	1	1
B737-800	36	160	18/12	1	1
B737-900	38	177	18/12	1	1
B787-8	41	274	40/25	2	2
A320-200, NEO	44.2	150	20/12	1	1
B777-200LR	45	375	50/30	2	1
B787-9	50	360	40/25	2	2
B777-300ER	52	451	50/30	2	1
A330-200,800	53	246	25/15	2	3
B787-10	56	411	40/25	2	2
A330-300,900	59	300	25/15	2	3
B747-400ER	60	442	40/25	2	3
B747-400	60	442	40/25	2	3
A350-900	61	315	25/15	2	3
A350-1000	70	369	25/15	2	3
A380 Main and upper deck	90	555	25/15	2	3
A380-Main deck	140	555	25/15	2	3

In order to figure out the time gap, the operational procedure is examined by each category. When compared each category side by side, the real activity time without positioning time does not show the large time gap. However, it was captured in a different handling way for some category. Thus, this research focuses on those categories: catering and refueling.

At first, the models by Airbus have a critical path relating to the catering activity. Catering activity cannot occur when de-boarding is on-going. Also, Boarding can start when the catering service is over. However, the models by Boeing have no regulation about the catering process. The 787 family is the only one which cannot handle de-boarding and catering together. The others (737, 777, and 747 family) can process de-boarding and catering together, especially the catering activity for the 737 is set up at time 1.

There is no critical path for refueling activity, but the model by Airbus has a rule. There is no overlapping time between refueling and de-boarding activity. However, some models by Boeing has an overlapping time between refueling and de-boarding activity. If there is no issue for safety, it should be acceptable. Table 4-19 shows the refueling time chart by the aircraft. One of the features is positioning time. The aircraft by Airbus for medium to the long range has longer positioning time than by Boeing.

Table 4-19 Refueling Time Chart

Aircraft	Start time	Positioning time (min)	Refueling time (min)	Positioning time (min)
B737-600	6	2	9	2
B737-700	6	2	9	2

B737-800	6	2	9	2
B737-900	6	2	9	2
B787-8	0	3	35	3
A320-200, NEO	7	2.5	16	2.5
B777-200LR	8	2	23	2
B787-9	0	3	35	3
B777-300ER	0	2	42	2
A330-200,800	0	8	32.5	8
B787-10	0	3	35	3
A330-300,900	1	8	34	8
B747-400ER	1	2	53	2
B747-400	10	2	28	2
A350-900	1.5	8	35	8
A350-1000	2.5	8	36	8
A380 Main and upper deck	12	5	34	5
A380-Main deck	12	5	34	5

Therefore, for the unity of the turnaround process, the rule should be defined and followed since the objective of the research has integrated the turnaround process.

For the catering activity, it follows the critical path by Airbus. It is reasonable based on the general flight experience. Thus, catering can start when de-boarding is over. Also, boarding can start when catering is over.

Regarding the refueling process, a few things should be assumed. Refueling can start when and if necessary. Also, if the aircraft can cover for medium to long ranges, then the positioning time for refueling should be eight minutes. The table 4-20, 4-21, and 4-22 show the revised aircraft turnaround process by Boeing. Table 4-23 and 4-24 shows the revised aircraft turnaround process by Airbus.

Table 4-20 Revised Typical Time of Turnaround Process: Boeing 1 (Short)

Activity (min)	B737-600	B737-700	B737-800	B737-900
De-boarding	Start: 0 (1)+6	Start: 0 (1)+8	Start: 0 (1)+9	Start: 0 (1)+10
Boarding	Start: 23 9+(1)	Start: 27 12+(1)	Start: 38 14+(1)	Start: 29 15+(1)
Catering	Start:5 (2)+5+(3)+8+(2)	Start:7 (2)+6+(3)+9+(2)	Start:8 (2)+5+(3)+10+(2)	Start:9 (2)+5+(3)+10+(2)
Cleaning	Start: 4 (2)+10+(2)	Start: 7 (2)+10+(2)	Start: 8 (2)+11+(2)	Start: 9 (2)+11+(2)
Unloading-fwd	Start: 0 (2)+3	Start: 0 (2)+4	Start: 0 (2)+5	Start: 0 (2)+5
Unloading-aft	Start: 0 (2)+5	Start: 0 (2)+6	Start: 0 (2)+6	Start: 0 (2)+6
Loading-fwd	Start: 20 4+(2)	Start: 20 6+(2)	Start: 20 7+(2)	Start: 20 8+(2)
Loading-aft	Start: 7 7+(2)	Start: 8 8+(2)	Start: 8 9+(2)	Start: 8 10+(2)
Refueling	Start:6 (2)+9+(2)	Start:6 (2)+9+(2)	Start:6 (2)+9+(2)	Start:6 (2)+9+(2)
Waste water	Start: 8 (2)+10+(2)	Start: 8 (2)+10+(2)	Start: 8 (2)+10+(2)	Start: 8 (2)+10+(2)
Supplying water	Start: 0 (2)+2+(2)	Start: 0 (2)+2+(2)	Start: 0 (2)+2+(2)	Start: 0 (2)+2+(2)
Total {pax}	33 min {108}	40 min {140}	44 min {160}	45 min {177}

Table 4-21 Revised Typical Time of Turnaround Process: Boeing 2 (Medium)

Activity (min)	B787-8	B777-200LR	B787-9	B777-300ER
De-boarding	Start: 0 (2)+6.9	Start: 0 (1)+7.5	Start: 0 (2)+9	Start: 0 (1)+9
Boarding	Start: 28.5 11.7+(1)	Start: 44 12.5+(1)	Start: 29 20+(1)	Start: 42 15+(1)
Catering 1	Start: 6.9 (2)+6+(1)	Start: 6.5 (2)+14.5+(3) +16+(2)	Start: 9 (2)+10+(1)	Start: 8 (2)+7.5+(3) +15+(2)
Catering 2	Start: 16 (2)+10.5+(1)	Start: 6.5 (2)+27+(2)	Start: 22 (2)+4+(1)	Start: 8 (2)+30+(2)
Catering 3	Start: 6.9 (2)+15+(1)	NaN	Start: 9 (2)+18+(1)	NaN
Cleaning	Available 8.9-28.3	Install: 3(2) Remove: 31.5(2) Available 5-31.5	Available 11-28	Install: 5(2) Remove: 36(2) Available 7-36
Unloading-fwd	Start: 0 (2)+16	Start: 0 (2)+[2]+18	Start: 0 (2)+20	Start: 0 (2)+24
Unloading-aft	Start: 0 (2)+12	Start: 0 (2)+14	Start: 0 (2)+16	Start: 0 (2)+20
Loading-fwd	Start: 18 16+(2)	Start: 29 14+(2)	Start: 22 20+(2)	Start: 28 20+(2)
Loading-aft	Start: 26 12+(2)	Start: 23 18+[2]+(2)	Start: 32 16+(2)	Start: 26 24+(2)
Refueling	Start: 0 (8)+35+(8)	Start:8 (8)+23+(8)	Start: 0 (8)+35+(8)	Start: 0 (8)+42+(8)
Waste water	Start: 14 (2)+10+(2)	Start: 0 (2)+15+(2)	Start: 14 (2)+10+(2)	Start: 15 (2)+16.5+(2)
Supplying water	Start: 0 (2)+10+(2)	Start: 0 (2)+17+(2)	Start: 0 (2)+10+(2)	Start: 0 (2)+11+(2)
Critical path	Service galleys 1 to 2, and Unloading to loading	NaN	Service galleys 1 to 2, and Unloading to loading	NaN
Total {pax}	51 min {274}	57.5 min {375}	51 min {360}	58 min {451}

Table 4-22 Revised Typical Time of Turnaround Process: Boeing 3 (Long)

Activity (min)	B787-10	B747-400ER	B747-400, -400 Combi, and -400 Domestic
De-boarding	Start: 0 (2)+10.3	Start: 0 (1)+11	Start: 0 (1)+11
Boarding	Start: 33.3 21.7+(1)	Start: 42 18+(1)	Start: 42 18+(1)
Catering 1	Start: 10.3 (2)+13+(1)	Start: 10 (2)+30+(2)	Start: 10 (2)+30+(2)
Catering 2	Start: 26.5 (2)+4+(1)	NaN	NaN
Catering 3	Start: 10.3 (2)+21+(1)	NaN	NaN
Cleaning	Available 12.3-32.3	Install: 10(2) Remove: 41(2) Available 12-41	Install: 10(2) Remove: 41(2) Available 12-41
Unloading-fwd	Start: 0 (2)+22	Start: 17 (2)+10	Start: 17 (2)+10
Unloading-aft	Start: 0 (2)+18	Start: 1 (2)+14	Start: 1 (2)+14
Loading-fwd	Start: 24 22+(2)	Start: 30 10+(2)	Start: 30 10+(2)
Loading-aft	Start: 36 18+(2)	Start: 42 14+(2)	Start: 42 14+(2)
Refueling	Start: 0 (8)+35+(8)	Start: 1 (8)+53+(8)	Start: 10 (2)+28+(2)
Waste water	Start: 14 (2)+10+(2)	Start: 21 (2)+21+(2)	Start: 21 (2)+21+(2)
Supplying water	Start: 0 (2)+10+(2)	Start: 1 (2)+47+(2)	Start: 1 (2)+14.5+(2)
Critical path	Service galleys 1 to 2, and Unloading to loading	NaN	NaN
Total {pax}	56 min {411}	70 min {442}	61 min {442}

Table 4-23 Revised Typical Time of Turnaround Process: Airbus 1

Activity (min)	A320-200, NEO	A330-200,800	A330-300,900	A350-900
De-boarding1	Start: 0 (2)+7.5	Start: 0 (3)+5	Start: 0 (3)+6	Start: 0 (3)+6.3
Boarding1	Start: 28 12.7+(2)+(1.5)	Start: 37.8 8.2+(4)+(3)	Start: 42 10+(4)+(3)	Start: 43.5 10.5+(4)+(3)
De-boading2	NaN	Start: 0 (3)+5	Start: 0 (3)+6	Start: 0 (3)+6.3
Boarding2	NaN	Start: 37.8 8.2+(3)	Start: 42 10+(3)	Start: 43.5 10.5+(3)
Catering 1	Start:7.5 (2)+4.7+(1.5)	Start:3 (5)+12+(3)	Start:4 (5)+6+(3)	Start: 4.3 (5)+15+(3)
Catering 2	Start:16 (2)+(2)+8+(1.5)	Start:3 (5)+5.8+(3)	Start:4 (5)+13+(3)	Start: 4.3 (5)+10.5+(3)
Catering 3	NaN	NaN	NaN	NaN
Catering 4	NaN	Start:3 (5)+29.8+(3)	Start:4 (5)+33+(3)	Start: 4.3 (5)+34.2+(3)
Cleaning	Available 9.5-28	Install: 5(3) Remove: 37.8(3) Available 8-37.8	Install: 6(3) Remove: 42(3) Available 9-42	Install: 6.3(3) Remove: 43.5(3) Available 9.3-43.5
Unloading-fwd	Start: 0 (2)+4.5	Start: 0 (2.5)+17	Start: 0 (2.5)+21.5	Start: 0 (2.5)+19.5
Unloading-aft	Start: 0 (2)+6	Start: 0 (2.5)+14.5	Start: 0 (2.5)+16.5	Start: 0 (2.5)+14.5
Loading-fwd	Start: 36 4.5+(1.5)	Start: 26.2 19.8+(2.5)	Start: 26.5 25.5+(2.5)	Start: 32 22.5+(2.5)
Loading-aft	Start: 34.5 6+(1.5)	Start: 29.5 16.5+(2.5)	Start: 32.5 19.5+(2.5)	Start: 37.5 17+(2.5)
Refueling	Start:7 (2.5)+16+(2.5)	Start: 0 (8)+32.5+(8)	Start: 1 (8)+34+(8)	Start: 1.5 (8)+35+(8)
Waste water	Start: 0 (2)+4+(2)	Start: 0 (2)+11+(2)	Start: 0 (2)+11+(2)	Start: 0 (2)+12+(2)
Supplying water	Start:8 (2)+5+(2)	Start:15 (2)+11.5+(2)	Start:15 (2)+11.5+(2.5)	Start: 16 (2)+17.8+(2)
Critical path	Deboarding-catering1&4-boarding-LPS	Deboarding-catering4-boarding-LPS	Deboarding-catering4-boarding-LPS	Deboarding-catering4-boarding-LPS
Total {pax}	44.2 min {150}	53 min {246}	59 min {300}	61 min {315}

Table 4-24 Revised Typical Time of Turnaround Process: Airbus 2

Activity (min)	A350-1000	A380 Main and upper deck	A380-Main deck
De-boarding1	Start: 0 (3)+7.4	Start: 0 (3)+14.2	Start: 0 (3)+8.9
Boarding1	Start: 42 3.6+[21.4]+(3)	Start: 59.3 23.7+(4)+(3)	Start: 110.7 14.7+[11.6]+(3)
De-boading2	Start: 0 (3)+7.4	Start: 0 (4)+8	Start: 0 (3)+13.4
Boarding2	Start: 42 21+(4)+(3)	Start: 59.3 13.3+[10.4]+(4)	Start: 110.7 22.3+(4)+(3)
Catering 1	Start: 5.4 (5)+17.6+(3)	Start: 12 (5)+42.3+(3)	Start: 12 (5)+42+(5.5)+46+(3)
Catering 2	Start: 5.4 (5)+19.4+(3)	Start: 12 (5)+24+(3)	Start: 12 (5)+24+(3)
Catering 3	NaN	Start: 8 (9)+34.5+(4)	NaN
Catering 4	Start: 5.4 (5)+31.6+(3)	Start: 12 (5)+22+(3)	Start: 12 (5)+22+(3)
Cleaning	Install: 7.4(3) Remove: 42(3) Available 10.4-42	Install: 15.2(2) Remove: 59.3(2) Available 17.2-59.3	Install: 14(2) Remove: 110(2) Available 16-110
Unloading-fwd	Start: 0 (2.5)+20.5	Start: 1.5 (2.5)+24	Start: 1.5 (2.5)+28
Unloading-aft	Start: 0 (2.5)+20.5	Start: 1.5 (2.5)+19	Start: 1.5 (2.5)+18
Loading-fwd	Start: 38 24.5+(2.5)	Start: 54 28.5+(2.5)	Start: 102 30+(2.5)
Loading-aft	Start: 38 24.5+(2.5)	Start: 60 22.5+(2.5)	Start: 110 22+(2.5)
Refueling	Start: 2.5 (8)+36+(8)	Start: 12 (5)+34+(5)	Start: 12 (5)+34+(5)
Waste water	Start: 0 (2)+12+(2)	Start: 2 (2)+28+(2)	Start: 1 (2)+28+(2)
Supplying water	Start: 16 (2)+17.8+(2)	Start: 34 (2)+25.5+(2)	Start: 33 (2)+25+(2)
Critical path	Deboarding-catering4-boarding-LPS	Deboarding-catering1-boarding-LPS	Deboarding-catering1-boarding-LPS
Total {pax}	70 min {369}	90 min {555}	140 min {555}

Table 4-25 Revised Turnaround Time and Number of Passengers

Aircraft	Turnaround Time (min)	Number of Passengers	Exclusion
B737-600	33	108	
B737-700	40	140	
B737-800	44	160	✓
A320-200, NEO	44.2	150	
B737-900	45	177	✓
B787-8	51	274	✓
B787-9	51	360	
A330-200,800	53	246	
B787-10	56	411	
B777-200LR	57.5	375	✓
B777-300ER	58	451	
A330-300,900	59	300	
A350-900	61	315	✓
B747-400	61	442	
A350-1000	70	369	
B747-400ER	70	442	✓
A380 Main and upper deck	90	555	
A380-Main deck	140	555	✓

Table 4-25 shows the revised turnaround time by aircraft model. Seven aircraft will be excluded if there is an equal turnaround time or same model.

In total 11 of the turnaround time process are selected for the simulation modeling. The time is distributed from 33 minutes to 90 minutes. The number of passengers should impact on the turnaround process, but the turnaround time is not always proportional to the number of passengers.

In the simulation process, each arrival will get the turnaround time assignment randomly from the turnaround time distributions.

4.3.4 Resources

The turnaround process get disruptions frequently. The reason for the disruption can be discussed as followings: It depends on the resource availability during the process. Furthermore, the turnaround process consists of huge amount of parallel and interrelated activities as well as the often incomplete and deficient information [79].

If the work environment can offer better resource utilization by processing the same work in less time, then the optimized turnaround time can be derived [78]. However, in the real world, it is hard to get the optimized turnaround time due to the constraints.

Table 4-26 [78] shows the three resource utilization cases and explains why the optimized turnaround time is not easy to achieve. Best case means a kind of supplying the resources unlimitedly. The worst case represents that there are only few resources to support. The real case is an intermediate stage of the best and worst case. It has a balanced number of resources to handle the traffic.

Table 4-26 Different Cases for Scenario Analysis [78]

Best case	Worst case	Real case
• Resources are always available • Surpluses appear	• Resources are not available in the required amount • Shortages appear	• Resources are well balanced • Bounded solution between the best case and worst case
• Expensive solution • Necessary resources are less than the available resources (cannot be used optimally)	• Cheap solution • Available resources are not adequate	• Find the suboptimal from the obtained solution

From the table 4-26, if the turnaround process is less sensitive to disruptions or delay due to late arrivals or severe meteorological condition, then optimizing the ground handling process is practicable [78]. Thus, it is necessary for the turnaround process to embed the involvement of resources for decision making.

It is evident that proceeding to the turnaround process is impossible without the resources such as truck, pallet, or loader. Thus, the three scenarios, as shown in table 4-26, will be applied into the simulation modeling process. The best case connects to an unlimited number of resources, and worst case connects to a specific small number of resources such as five. In order to find a balanced condition for real case, the sensitivity of resources should be analyzed. It will be discussed in Chapter 5 again.

CHAPTER 5. SIMULATION MODELING

Chapter 4 reviewed how to define the required inputs for the integration of the turnaround process within the current physical capacity. Thus, the historical flight data has been analyzed and used to define operational scenarios.

Furthermore, data regarding turnaround activities and time for each selected aircraft model have been evaluated. The flight arrival of the selected airport and the resulting operational scenarios can be seen in section 4.1 and 4.2. Section 4.3 includes the turnaround process time for each aircraft model.

This chapter consists of the simulator development process employing the inputs from chapter 4 and setting up the experiments required for hypothesis testing. The simulation modeling process will do the experiments with an airport in the United States. As mentioned in chapter 4, the selected airport is Atlanta Hartsfield-Jackson Airport because of the number of passengers and scheduled flights.

There are multiple stages in terms of simulation modeling. In the first stage, there is an explanation of the sequence and dependency of ground handling activities. The second stage shows a description of a critical path based on the first stage. The conceptual modeling analysis will be represented in a third stage based on the first and second stage. The development process of the simulator follows on the conceptual modeling analysis. In the fourth stage, there is more explanation of the data analysis with the relevant factors. The fifth stage shows a description of Hartsfield Airport and the handling market in Atlanta. Then, the last stage illustrates the variables to be analyzed.

5.1 The Sequence of Ground Handling Activities

When reviewed, the process of aircraft turnaround in Chapter 2 includes all ground activities that should be completed at an aircraft while parked at a terminal gate. It begs the question: how to determine the sequence of aircraft ground handling activities. In order to answer the question, it is necessary to figure out the dependency of the ground handling activities. The interrelation of ground activities should be reviewed for the on-time performance of aircraft departure.

For safety, some activities can take place independently of each other, while others must occur in sequence. For example, the rear-hold and front-hold off-loading with two lower-deck loaders may take place independently [53]. On the other hand, deboarding the passengers and cleaning process should occur in sequence.

Figure 5-1 shows the position of each service vehicle when the turnaround activity is on-going. As shown in figure 5-1, most activities existed in the sequence. In other words, those cannot start until the previous activity has completed. For example, ‘unload the first pallet’ cannot be processed until ‘open the hold door’, and ‘position the loader’ have completed [53].

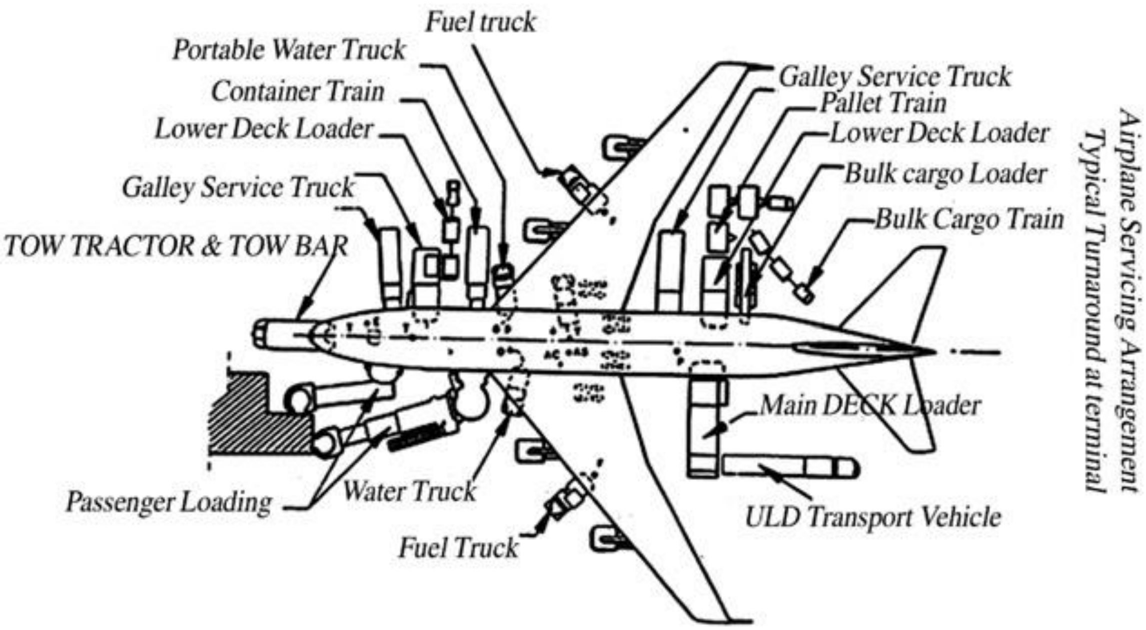


Figure 5-1 Positioning the Activities during Transit/ Turnaround [53]

Figure 5-2 shows the dependence among the ground handling activities. It can show that there are restrictions on which activities must not begin until others end. For example, the boarding process cannot start until the end of catering and cleaning activities. Those sequenced processes become the critical path [26]. In section 5.2, the critical path for the operational scenario will be discussed.

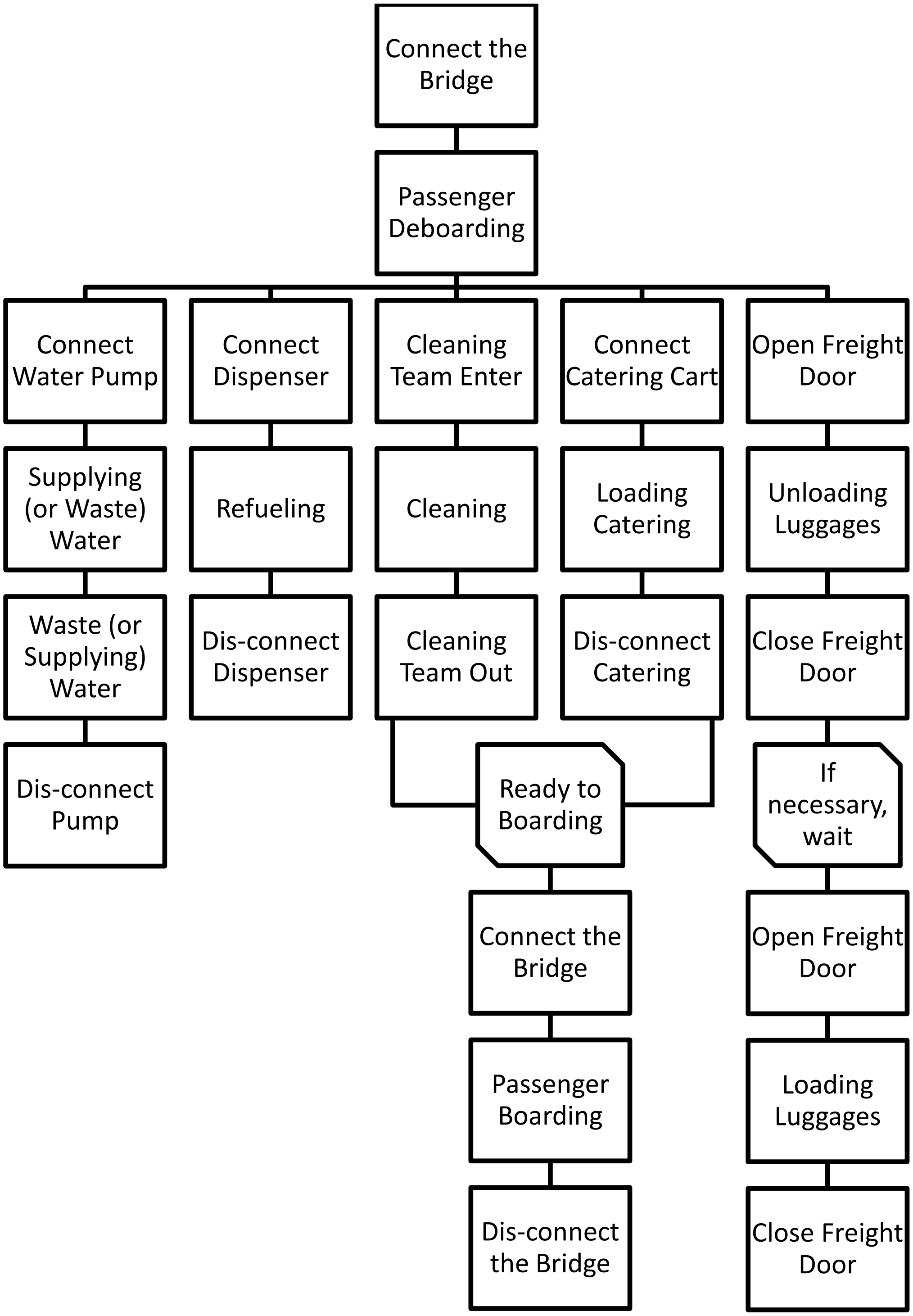


Figure 5-2 Interdependency among the Turnaround Activities [26],[34]

5.2 Critical Path

In the field of project management, critical path represents defining a sequence of tasks in a project [54]. It connotes that the tasks cannot be delayed and cannot affect the end time of the project.

As discussed in chapter 4, the establishment of the critical path for the turnaround process is required to decide the aircraft turnaround time. The critical path is a list of interrelated activities, so it requires the important time to complete. Thus, the effective management of the activities can contribute to reduced turnaround time [26]. Decreasing the turnaround time will result in the reduced turnaround cost.

In general, the passenger and cabin activities are included in the critical path: Cleaning cabin can proceed after passenger's deboarding, and passenger can board after completion of the cleaning activity. In addition, some activities that cannot proceed simultaneously are included in the critical path: (deboarding and boarding), and (unloading and loading). Another example would be the critical path from safety regulations. Some aircraft cannot start refueling activity until the completion of deboarding.

Figure 5-3 shows the critical paths. There are two main critical paths: passenger and cargo. The first critical path is passenger deboarding, cabin services and cleaning, and passenger boarding. The second critical path is unloading cargo and loading cargo.

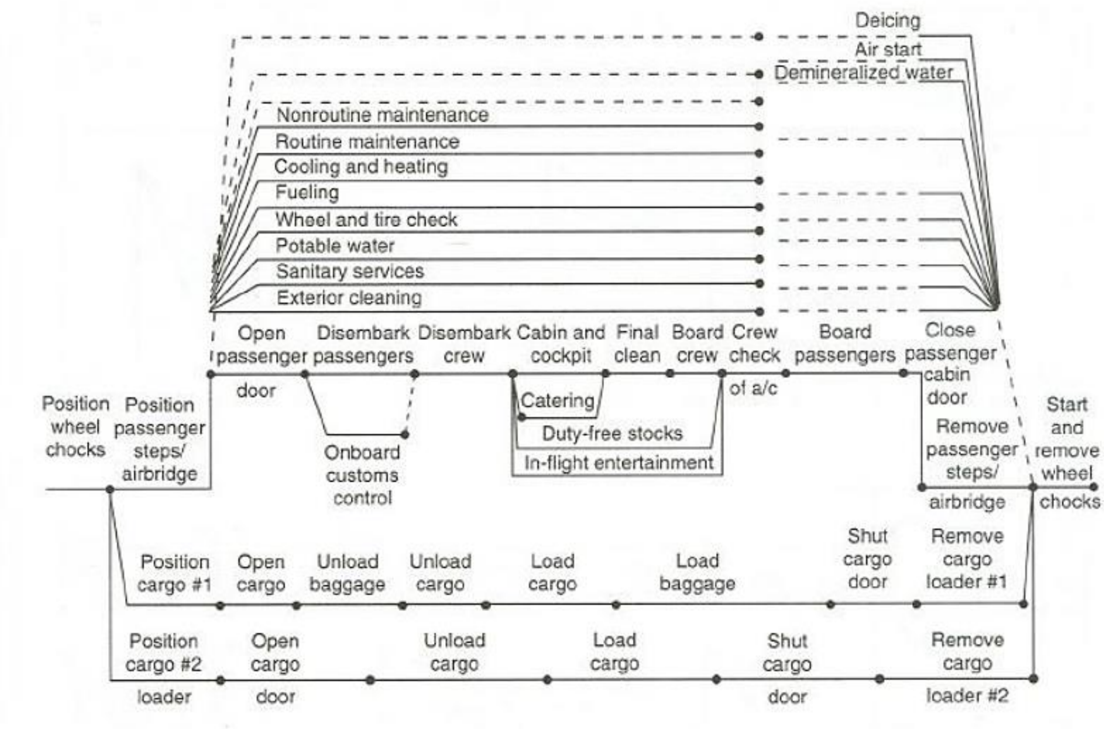


Figure 5-3 Critical Path in Aircraft Turnaround [11],[60]

Figure 5-3 illustrates some activities can be performed independently such as water activity.

5.3 Model Development

In section 5.1 and 5.2, the ground handling work structure is analyzed as well as its connectivity with the critical path. Thus, this section will how to implement it into the discrete event simulation of the aircraft turnaround process.

5.3.1 Conceptual Modeling

In order to implement the simulator, the conceptual model is a required step containing the essential requisites of the aircraft turnaround process. The essential requisites mean the sequence and interdependence of ground handling activities and their critical path to a stable turnaround process.

5.3.1.1 Modeling Assumptions

The aircraft turnaround process is not a natural process. It is a complex process where there are many variables. Some assumptions have been stated in order to make the problem solvable.

- Aircraft
    - Arrival is the first event
    - Assign the model randomly among 11 aircraft types
- Ground facilities
    - Move along the available roads
    - Move from one aircraft position to the other
- Human resources
    - Move together with ground facilities, i.e., truck, loader
- Passengers
    - No late passengers
    - No disabled passengers
    - Do not care about the gender and age of passengers

5.3.1.2 Modeling Components

For the aircraft turnaround simulation, the flight arrival occurs first. Then, the passengers should de-board, and their luggage should be unloaded. For the next flight departure, the aircraft needs to clean inside, and load the food the next flight's passengers. In addition, it requests supplying fuel and water. Lastly, the passenger will board, and their luggage will be loaded. After completion of all the activities mentioned, the aircraft is ready for departure. Figure 5-4 shows the structure of those activities by simplification.

The figure shows the blocks are color-coded by their characteristics. Red colored blocks mean the start and end of each aircraft turnaround process. The turnaround process starts with the flight arrival and finishes when the flight is ready to depart and proceed to take-off. Blue edge blocks represent the preparation before the execution of each activity. Orange edge blocks show the post-processing steps after the execution of each activity. Grey colored blocks illustrate each ground handling activity.

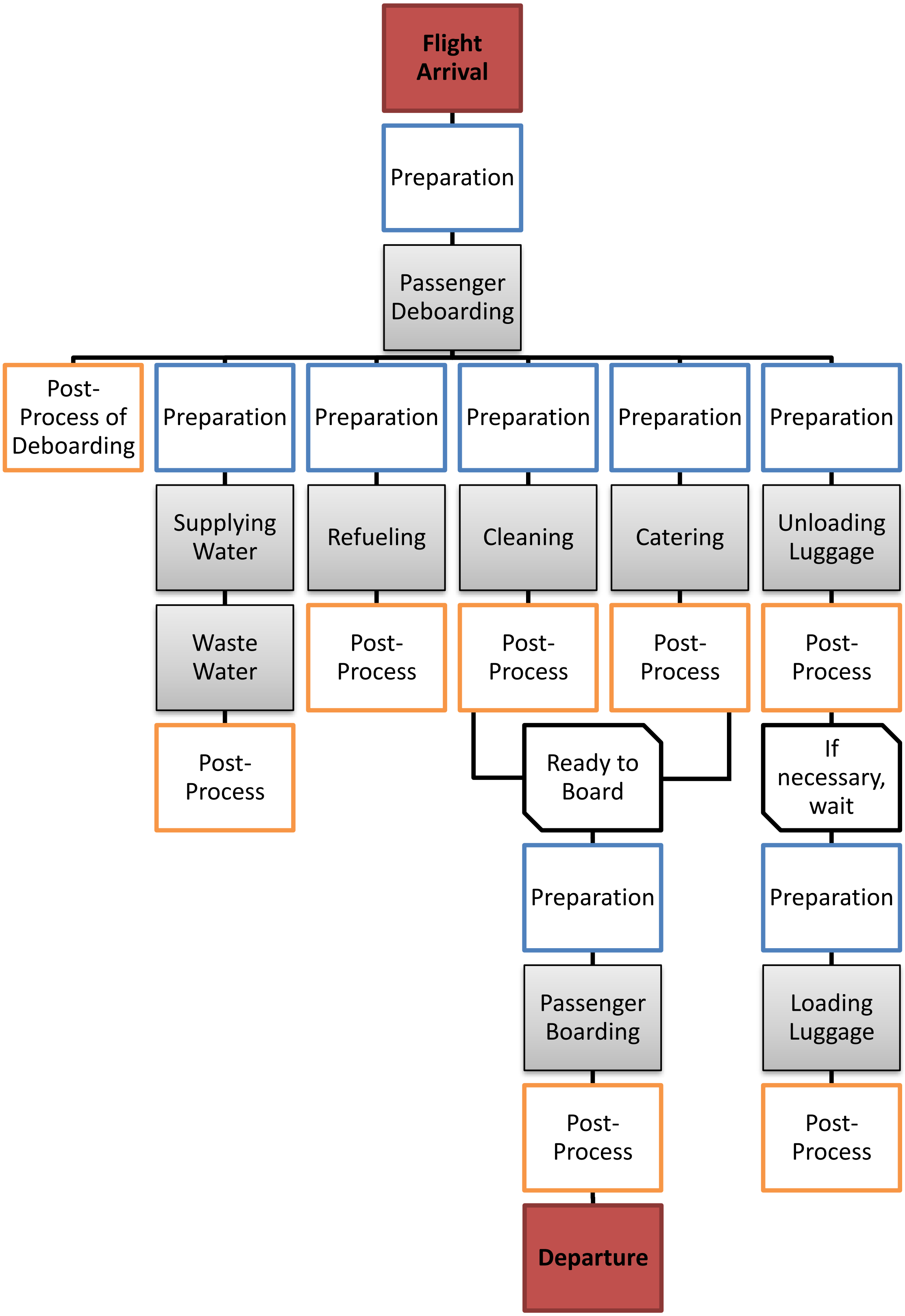


Figure 5-4 Simplified Work Structure for Discrete Event Simulation

The first research question, assessment of the stability of the aircraft turnaround process by integrated approach should be addressed by tracking of two metrics: the number of on-time flights and delay time. Therefore, the expected outputs are primarily defined as the number of delayed flights, the number of on-time flights, the time of delay and the real departure time vs. the scheduled departure time.

5.3.2 Simulator Development

This section describes the implementation of a simulator that handles the aircraft turnaround process. The implementation of the simulator is realized with Python and PyQt.

Qt provides that ue of signals and slots to communicate between objects [80]. The use of signals is a good means to communicate in the turnaround process like the real world. As Qt provides this capability out of the box, it is chosen as the sandbox for the implementation of the simulator. Further, as python provides a quick development and testing environment, the python alternative of Qt, PyQt, is chosen as the backend for the simulator.

The framework implements a Discrete Event Simulator (DES) that is realized through a core **Simulation** object, which is composed of three other objects, a **Queue**, a **ResourceManager**, and a **Scheduler**. Figure 5-5 shows the class diagram of the entire simulator. The simulation core framework is supported by a set of utilities that provide general functionalities that are independent of the process being simulated. In the current dissertation, the aircraft turnaround process is modeled as a discrete event process.

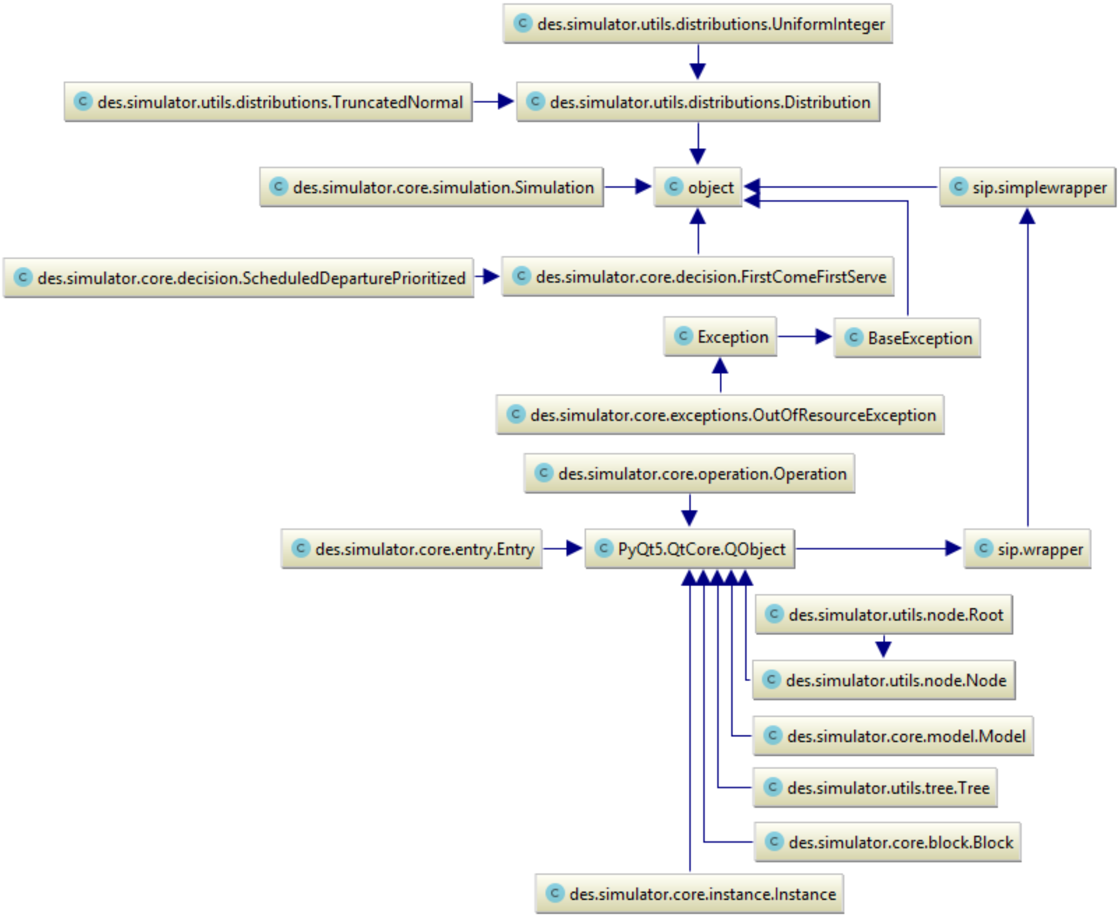


Figure 5-5 Class Diagram of Entire Simulator

The **Queue** object stores a queued set of aircraft that are currently being processed. It transmits signals from the aircraft model when ground handling activities are either begun of terminated. The **ResourceManager** object handles all the resources, such as how many resources are available, the allocation of resources and also manages the request of resources from the aircraft model. The **Scheduler** object handles the arrival schedule of the flights. Figure 5-6 shows the class diagram of the Core module of the simulator. The details of each element will be discussed in sub-sections thereafter.

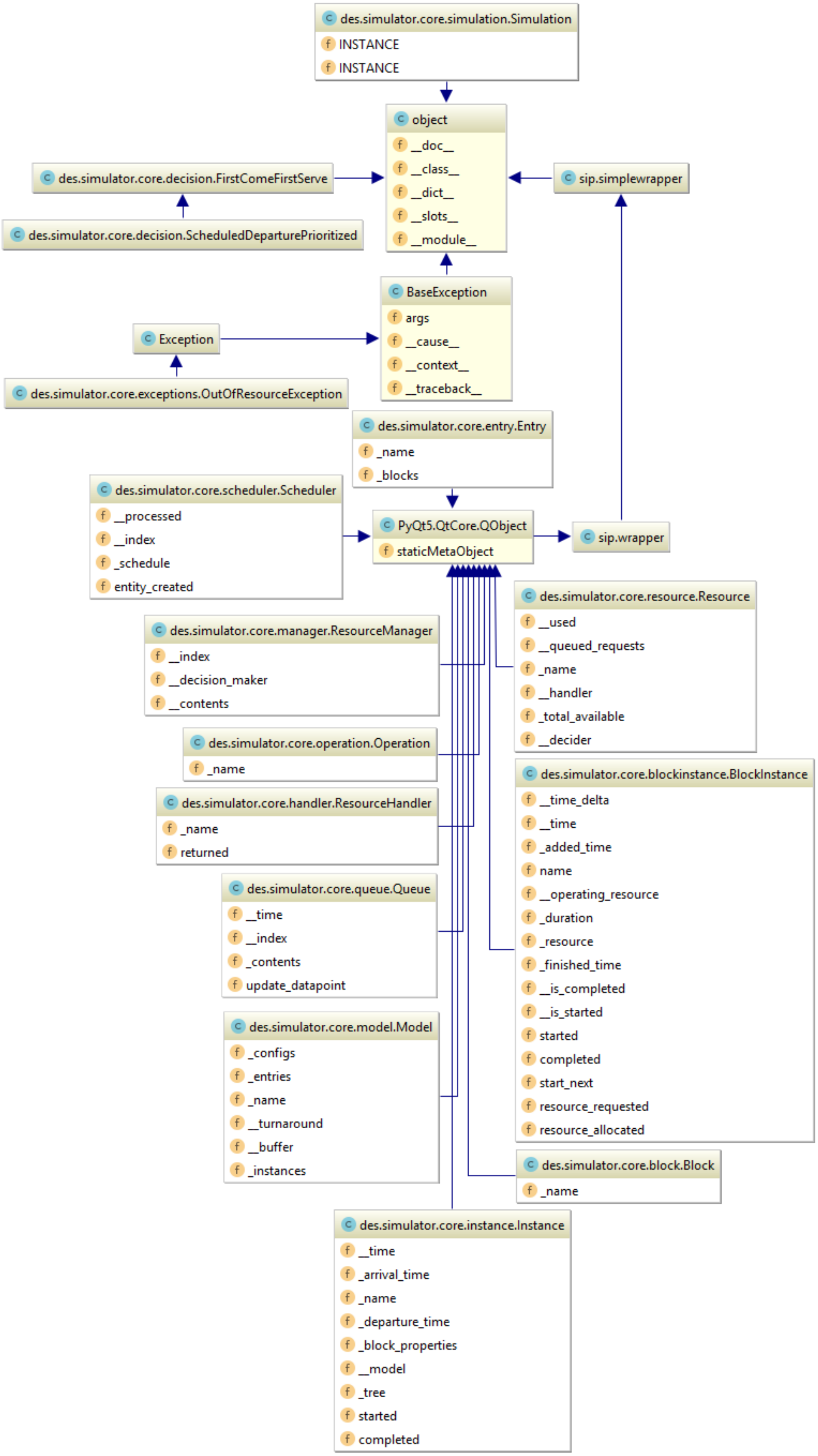


Figure 5-6 Class Diagram of Core

Figure 5-7 shows the class diagram of the Utilities module. The framework utilizes a sequence graph to determine the order in which the ground handling activities are to be executed. This is realized through the utilities module, which includes the **Tree** and **Node** objects. Although technically, a graph, the processing sequence of events can be realized as a structured tree with each node of the tree representing a ground handling event.

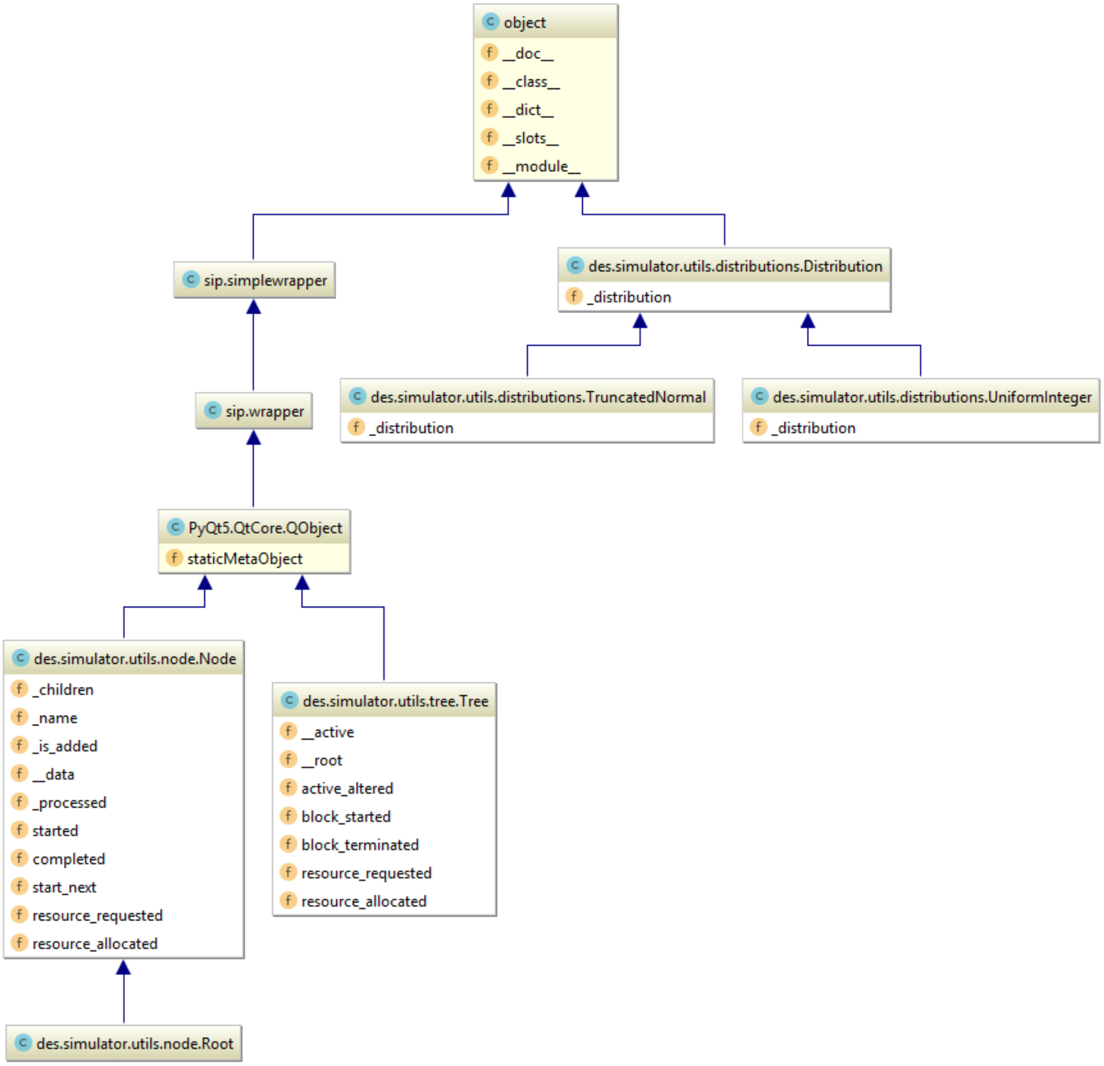


Figure 5-7 Class Diagram of Utilities

5.3.2.1 Queue

The Queue is implemented as a subclass of the base QObject. This queue will emit a signal indicating the completion of each ground processing activity. The signal relies on the presence of an emitter and a listener (slot), hence the terminology signal-slot [81]. When the activity finishes processing, the simulation documents the performance of that aircraft model tabulating the model’s actual ground processing duration, its ideal duration, and also the duration associated with each step of the processing.

The primary purpose of the queue is mainly to hold the set of aircraft being simulated at the simulation instance, i.e., the instantaneous time in the simulation environment. Thus, the queue is comprised of a set of aircraft model instances with the instances representing a concrete aircraft, i.e., an aircraft that has arrived and is ready for ground processing. The way the queue works is described in the simulation work.

5.3.2.2 ResourceManager

The primary function of ResourceManager is mainly to hold the resources. It comprises “resource stores.” Each resource store can be viewed as being a warehouse for a particular type of resource. The simulation capability is generalized in a manner such that each resource type can rely on the presence of a different type of resource and hence the necessity for a manager. The number of available resources for one type of resource lies on the positive integer line and varies between zero to infinite. The number of resources can also be modeled as being time-variant.

In this case, a daily schedule (24hours) is divided into four slots with each period having a different number of resources available. It enables time-varying resource allocation so as to address the distribution in aircraft arrivals.

Table 5-1 Time Shift Period

Time Slot 1	00:00 - 06:00
Time Slot 2	06:00 - 12:00
Time Slot 3	12:00 - 17:00
Time Slot4	17:00 - 00:00

Resource stores and resources have the ability to handle their own behavior. This is accomplished through the implementation of custom deciders and handlers. To explain what the decider and handler do, consider the following example: a fire truck station (resource store) where fire trucks (resource) are stored. Whenever there is a call for a fire truck, the station sends out one of the fire trucks, i.e., makes a decision of which fire truck has to be deployed. That is what the decider does.

The handler, on the other hand, is a property of the resource, it dictates the manner in which the resource handles its function. For example, if the user wishes to “handle” the consideration for traversing from point A to point B or physics or mathematical constraints on the behavior of the resource, a custom processing unit can be attributed to the resource handler that performs a real-time logic computation to determine the emergence in resource behavior.

Thus, in summary, the handler specifies the way the resource travels, detects how long it will take and how agile they are, and the decider decides on where to send a resource and which resource to send. Two different decision criteria are evaluated in the current implementation. These are the two operational strategies: First Come First Served (FCFS), Schedule Departure Time (SDT).

The FCFS strategy relies on an order queue, where the aircraft model ground processing block instances are ordered based on their demand time. For each block instance, the resource store assigns the requested number of resources such that:

$$Used\ number\ of\ resources\ <\ Total\ number\ of\ resources$$

Moreover, the resource store creates the requested number of resources with the handler defined by the user. Resource creation is handled dynamically thereby optimizing for memory.

5.3.2.3 Scheduler

The Scheduler is also implemented as a subclass of a QObject to enable the emission of aircraft model instance creation signals. The scheduler reads data from an input data file that defines the arrival schedule for the airport. The ideal input file would indicate the arrival of the aircraft model and the time at which the aircraft is scheduled to arrive.

Delays in arrivals are not considered in the current analysis. As information regarding the model of the aircraft is absent in the case considered, aircraft models are assigned randomly, with uniform probabilities, to the arrival slots.

5.3.2.4 Model

The aircraft model forms an abstract description of the aircraft and also an abstract aircraft container dictating the sequence of ground processing events. Each model is aware of all the aircraft exist in the simulation world. Although it is possible to create the aircraft model and a model container separately, for simplicity, an attributed implementation for the container is chosen, i.e., the container is a class attribute of the model object.

Each model is a configurable object. The configuration dictates the sequence of ground processing events that are associated with the aircraft. The current implementation utilizes a hierarchical representation of the events, i.e., the events themselves are composed of sub-events. This is typical of the ground handling process where events such as deboarding are divided into multiple phases. Each high-level event is termed as an entry, and the entries are composed of a set of phases, termed blocks.

The simulator, during its execution, structures the blocks to be executed in a graphical (tree) structure and traverses the tree over the course of the execution. In terms of the implementation, each model is associated with an input file dictating the model of the aircraft. The structure of the input deck defining the aircraft is as illustrated in Appendix D.

Although the model represents an abstract aircraft, in conjunction with the scheduler, it is capable of creating real instances of aircraft. This is accomplished by having the scheduler request the creation of an instance and by indicating the type of model that is to be initialized.

The model, having complete knowledge of the aircraft's ground handling configuration, instantiates a tangible version of the aircraft that can be simulated. With each tangible aircraft, the model creates the associated instance of the events, i.e., entries, and the instances of the blocks, i.e., block instances.

5.3.2.5 Tree

The sequence associated with the execution of the ground processing activities is stored in the form of a tree within the aircraft instance. The root of the tree indicates the first activity that begins at the local timestamp of zero, provided availability of resources.

The tree is structured in such a manner that multiple root nodes can exist. Constraints in the form of relationships between events can be established in the tree. These appear in the form of edges connecting nodes in the tree. Hence the tree can be viewed as a graph. Support for numerical relationships between the block instances is also provided by the framework.

During the event processing, the simulator traverses the tree identifying the block instances that are to be executed at the local instant of time. This process repeats until all the block instances have been successfully executed.

The signal-slot framework is used to communicate between the executing block instance and the simulator and this, in turn, enables the acquisition of the next set of block instances that are to be executed. The process repeats until there are no block instances left to execute.

5.3.2.6 Block

A block is a phase of a ground handling activity, for example, the preparation phase of the deboarding, or the execution phase of the refueling activity. Each block is defined by duration and the resource required to execute the block. Probabilistic representations for the durations are also permitted by the framework.

5.3.2.7 Entry

Each entry represents a ground processing activity. The activities can be deboarding, boarding, unloading, loading, cleaning, catering, refueling, supplying water and waste water. The entry is composed of a set of blocks that define the phases associated with each activity.

5.3.3 Data Format

The simulator requires a total of four types of input data files and produces one output file that stored the entire process of simulation. The format of all the files is csv.

- Input data file
    - Flight Arrival

      It consists of the date and flight arrival time. Appendix B shows the format of flight arrival.
    - Resource

      It consists of the resource name and the number of resources by the time slot. Appendix C shows the format of resource.
    - Model

    It consists of phase (ground handling activity), sub-step (sub-process of the activity) and its time, resource (a type of resource), and the aircraft model. Appendix D shows the format of model.

  - Time

    It consists of the turnaround time of each aircraft model and their schedule variability buffer. Appendix E shows the format of turnaround time and schedule variability buffer.

- Output file
  - It has the entire tracked data of the turnaround process.
    - Scheduled time and real-time of each ground handling activity
    - Scheduled departure time and real departure time
  - Appendix F illustrates the format of output file.

5.4 Design of Experiment

Design of Experiments (DoE) is a systematic methodology to identify the factors influence the output of a system. DoE allows us to estimate the significant impact of the factors and their interactions. Each factor has its own value, called level [58]. DoE offers the evaluation of the various factor's level, and identification of the factor's leverage as a studied metric. To capture the critical factors, it should be a key that implementing the well-structured experiments. Hypotheses, which are proposed to proceed with this research, help us properly design experiments because experiments are used to test those hypotheses.

Before evaluating the hypotheses, the preliminary step is the definition of parameters. Kolukisa [11] conducted doctoral research that evaluated the aircraft turnaround process in the framework of airport design and represented the analysis of past flight data to support it. It shows the data analysis with the aircraft model, gate, season, time of day, the day of week and destination, which are recorded by the ground handling company.

Thus, this research tries to include those variables and more: aircraft model, level of congestion, day, schedule variability buffer, operational strategy, and weather. Level of congestion and day contain the seasonal and rush hour effects. Most of them are already discussed in chapter 4 to select representative scenarios but will be summarized here.

5.4.1 Environment

Before pointing out all variables, the environment of those variables should be mentioned. The airport is the main stage of the aircraft turnaround process. Thus, the simulation of the turnaround process occurs in the environment where similar to the airport. Thus, one of the airports in the United States is necessary for the environment.

The Atlanta Hartsfield-Jackson Airport plays a role as a hub airport in the southern region. It is ranked #1 in passenger traffic and scheduled flights. Also, it is ranked #7 in an average delay of departures and #23 in an average delay of arrivals. The table 5-2 shows the Atlanta airport’s on-time performance.

Table 5-2 Atlanta Hartsfield-Jackson Airport: On-Time Performance (Major U.S. Carriers only, domestic [57])

% on time	2011	2012	2013	2014	2015	2016
Departure	80%	84%	79%	79%	82%	83%
Arrival	80%	85%	81%	81%	84%	86%
Average delay time (min)						
Departure	56.26	52.15	53.39	50.81	54.81	57.08
Arrival	59.60	59.24	60.40	60.62	65.47	69.00
% Cancelled						
Total	1.67%	0.58%	0.73%	1.62%	0.68%	0.42%

Since the Atlanta Hartsfield-Jackson Airport has been labeled as a strategic location, it is chosen as the environment.

5.4.2 List of Parameters

5.4.2.1 Aircraft Model

Each airline has different aircraft models for flight operation. To select the mostly used aircraft, statistics identify 11 different aircraft models as relevant. Aircraft models are randomly selected in the simulation for each flight arrival.

Table 5-3 shows the selected aircraft models, their turnaround time and a number of passengers.

Table 5-3 Selected Aircraft Model for the Simulation Modeling

Aircraft	Turnaround Time (min)	Number of Passengers
B737-600	33	108
B737-700	40	140
A320-200, NEO	44.2	150
B787-9	51	360
A330-200,800	53	246
B787-10	56	411
B777-300ER	58	451
A330-300,900	59	300
B747-400	61	442
A350-1000	70	369
A380 main and upper deck	90	555

5.4.2.2 Level of Congestion

In general, the summer season has more traffic and, therefore, more delays than other seasons. Thus, regarding the seasonal effect, two representative months are selected in section 4.1 and 4.2: July and November. In here, the seasonal effects of traffic demand is called the level of congestion.

There are two types of level of congestion: busy and normal. July plays a representative month for the busy level of congestion, and November plays a representative month for the normal level of congestion.

5.4.2.3 Day

In section 4.1 and 4.2, the representative days were discussed in order to capture the feature of weekends and weekdays. In general, the passengers usually have more travel on the weekends than the weekdays.

In terms of the Atlanta airport's historical data, two days were selected: Tuesday and Friday. Tuesday works as the representative day of weekdays, and Friday works as the representative day of weekends.

5.4.2.4 Schedule Variability Buffer

In section 2.2.3, schedule variability buffer was introduced. It functions as a buffer time to absorb arrival delays and unexpected delays from the ground handling activity. There are a total of three cases:

- Ideal: Schedule variability buffer = 0
- Robust: 0 < Schedule variability buffer < max
- Largest: Schedule variability buffer = max

5.4.2.5 Operational Strategy

There are two operational strategies for aircraft queuing. The first strategy is ‘Scheduled Departure Time.’ It means the aircraft that has the earlier scheduled departure time takes a priority for the turnaround activity. The second strategy is 'FCFS (First-Come-First-Served).' It represents the aircraft which first arrived takes a priority for the turnaround activity.

5.4.2.6 Number of Resources

The number of resources for each activity is one of the exciting variables to figure out. Since this research has suggested a new operational frame 'Integration of the turnaround process,' counting the total number of resources is limited due to insufficient information.

Therefore, this research will examine resource dependency and analyze the sensitivity of a number of resources. Three different cases are already discussed in section 4.3.

- Best case
    - Supplying the resources unlimitedly

      $Number\ of\ resources\ =\ unlimited$
- Worst case
    - Supplying the resources limitedly

      $Number\ of\ resources\ =\ min$
- Real case
    - Balanced number of resources to handle the traffic

      $min\ <\ Number\ of\ resources\ <\ unlimited$

5.4.2.7 Weather

Weather conditions play a significant role in order to determine airport capacities. Chicago O'Hare airport announced the notable weather events or stressors. Since those have impacted the airport operations and infrastructure, every stressor is potential factors to make a delay. Here is the list of the weather stressors [86]:

- Heavy precipitation and flooding
- Heavy seasonal snow
- Blizzards
- High winds
- Lightning and thunderstorms
- Ice

The reported impacts by the weather stressors are as followings [86]:

- Flooded facilities and equipment
- Power outages
- Disrupted access points
- Damage to electrical systems

Thus, the weather is a critical variable to decide if the operational scenario is nominal or off-nominal. It assumes that the nominal operational scenario is flight operations under usual and ordinary weather conditions. On the other hand, the off-nominal operational scenario will be flight operations under severe weather conditions which require additional or delayed activities in the aircraft turnaround process.

In section 5.4.2.2, the busy season selected July and the normal season selected November. However, the weather delay is common in the winter season. Thus, a total of five months including two representative months and the winter season are evaluated for the off-nominal weather scenario:

- July
- November
- December
- January
- February

Table 5-4 includes the total number of delayed flights and the number of delayed flights due to the weather. The last column shows the ratio of the weather. January has the highest one: 9.769 %.

Table 5-4 Number of Delayed Flights due to the Weather and the Ratios

Month	**Total Delayed Flight**	**Delayed Flight due to the weather**	**Ratio**
July	13974	898	6.43%
November	7012	250	0.34%
December	10486	483	4.61%
January	10932	1068	9.77%
February	7217	58	0.80%

However, counting the number of delayed flights is not enough to show the influence of the weather. Thus, the delay time due to the weather and its proportion is evaluated from the BTS historical data.

Table 5-5 illustrates the total delay time and the delay time due to the weather for each month.

Table 5-5 Cumulative Delay Time due to the Weather and the Ratios

Month	Total Delay Time (min)	Delay Time due to the Weather (min)	Ratio
July	515784	29474	5.71%
November	132611	923	0.70%
December	330593	51297	15.52%
January	512384	66417	12.96%
February	187028	2068	1.11%

When compared based on the ratio, December has the highest portion due to the weather. Therefore, for the off-nominal scenario, 15.52% will be applied to the aircraft turnaround process as a delay component. In summary, the variable weather has two types of scenarios:

- Nominal
    - No delay due to the weather
- Off-nominal
    - 15.52% additional delay due to the weather

5.4.2.8 Summary of Parameters

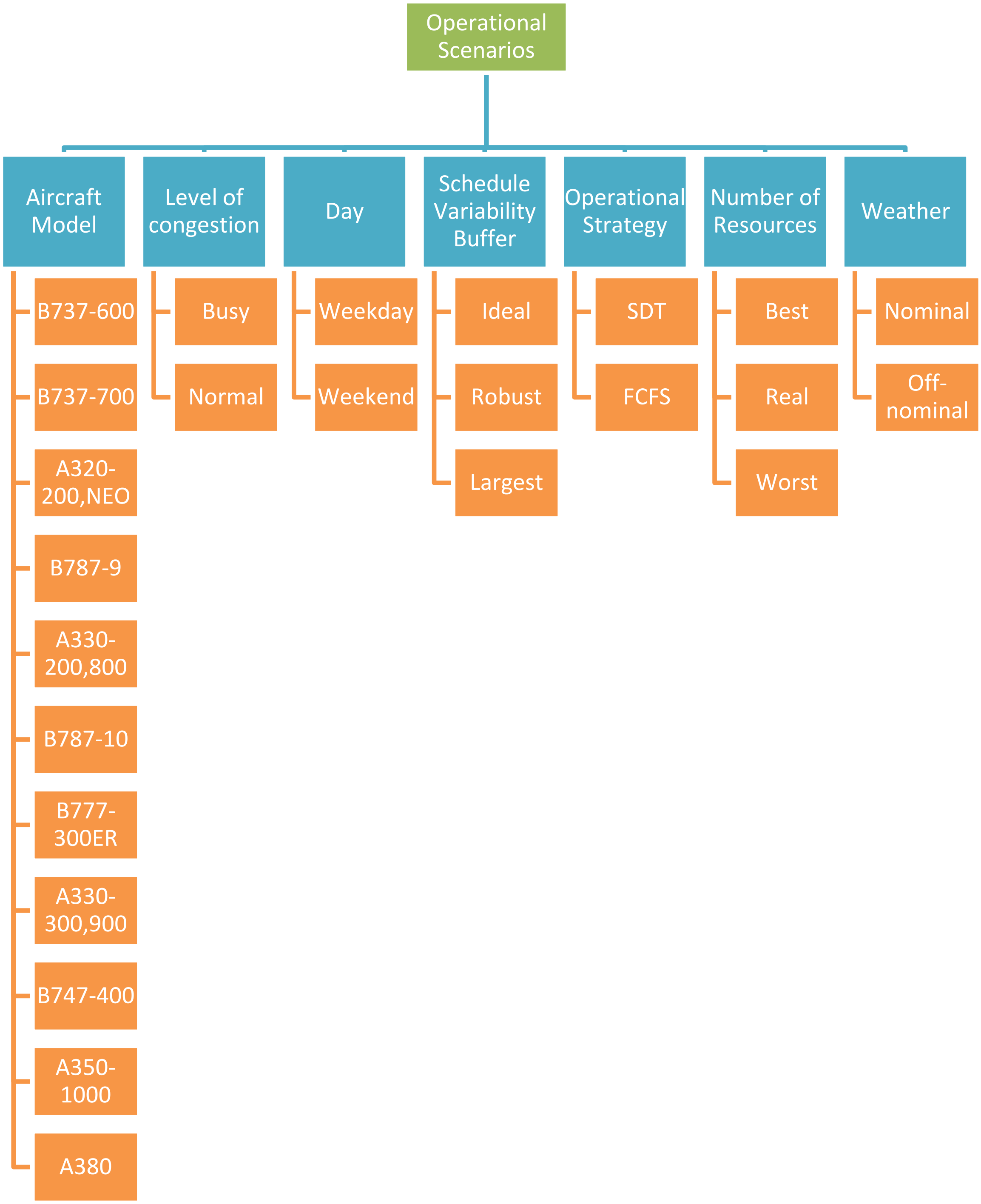


Figure 5-8 Summarized View for Experiments

Figure 5-8 shows the summarized view of the design of the experiment. The second level represents the name of the parameters. Except for the aircraft model, the children of the second level show the available options for the operational scenarios to run the simulation. Aircraft model contributes to the arrival schedule of simulation. Their children are selected randomly when the arrival takes place.

5.5 Summary

Chapter 5 reviewed the work structure of ground handling activities and their critical path in section 5.1 and 5.2 for the sophisticated simulation modeling. Then, Section 5.3 illustrates the implementation process of the simulator with its conceptual model. Since the simulator is ready to run, section 5.4 discusses the design of the experiments. The environment of the turnaround process is explained in section 5.4.1, and the variables for the simulation are evaluated in section 5.4.2. The performance of the simulator with those components will be analyzed in chapter 6.

CHAPTER 6. PERFORMANCE EVALUATION

In order to implement the simulation of the aircraft turnaround process based on the suggested approach, chapter 5 discussed the structure of the turnaround process to the methodology and operational scenarios. Section 5.1 and 5.2 analyzed the work structure of ground handling activity and the connectivity from the critical path, and section 5.3 showed the development process of the simulator.

In terms of the design of the experiment, section 5.4 introduces the environment of the simulation and the list of variables to make the operational scenarios. The primary objective of this chapter is the performance of simulator with those scenarios. The tracked outputs will be shown, and then the impact of each variable will be analyzed and discussed in the context of proving/disproving the previously stated hypotheses (see chapter 3).

6.1 Key Components of Experiments

Figure 6-1 illustrates the key components of experiments. Experiments are designed based on the data analysis. The data analysis compromises flight schedule analysis, turnaround process analysis and definition of operational scenarios. The process of flight schedule analysis and turnaround process is detailed in Chapter 4. Also, Chapter 5 describes the setup of the experiments.

In terms of operational scenarios, an ‘Operational strategy’ defines two use-cases defined by the prioritization scheme. The results of these use-cases are discussed in this chapter.

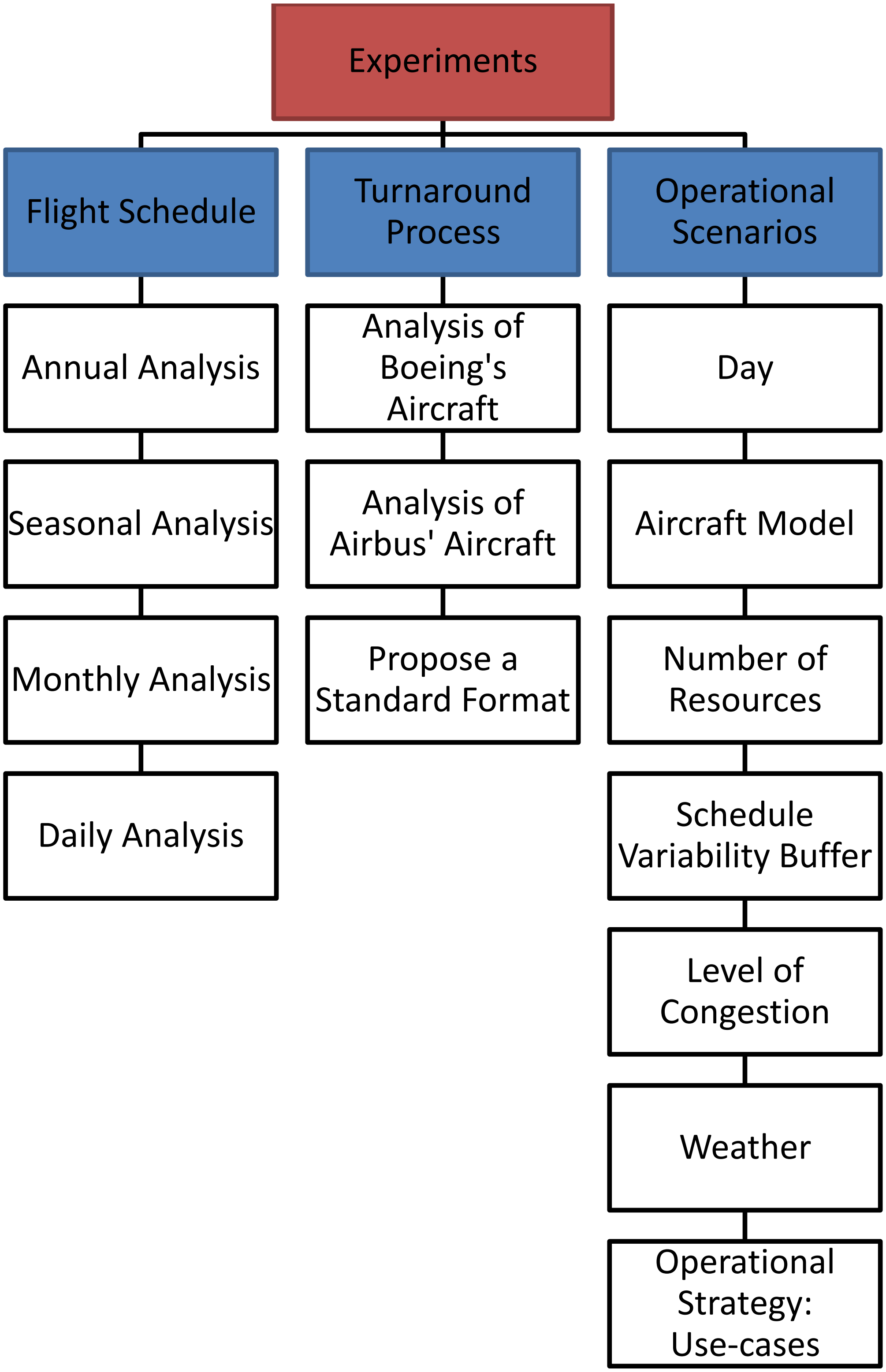


Figure 6-1 Key Components of Experiments

6.2 Boundary Condition

Prior to the discussion of the performance of the simulations, the assigned values of the variables in section 5.4.2 are introduced. Seven critical variables were identified. They are:

- Aircraft model
- Level of congestion
- Day
- Schedule variability buffer
- Operational strategy
- Number of resources
- Weather

Every variable has a clear definition of their value (or option) except two variables: number of resources and schedule variability buffer, which are defined by their minimum or maximum values. Thus, for those variables, the assignment of the boundaries are discussed.

6.2.1 Number of Resources

There is a total of three cases for the number of resources:

- Best case:

$$\text{Number of resources} = \text{unlimited (infinite)}$$

- Worst case:

$$\text{Number of resources} = \text{min}$$

- Real case:

$$\text{Worst case} < \text{Number of resources} < \text{Best case}$$

The best case has a clear definition, which represents an unlimited number of resources. The scenario of the best case may be unrealistic, but it will be tested in the simulator for the purpose of sensitivity analysis. Worst case has an unclear definition, which represents the minimum number of resources. In general, the minimum number of a positive integer is one. However, to handle Atlanta’s traffic volume, a single resource is not a reasonable choice for a minimum number of resources. Thus, in order to find the minimum number of resources, the simulation was utilized.

To see the impact of the number of resources, all parameters except the number of resources are fixed. The fixed parameters are as followings:

- Level of congestion

  Normal
- Day

  Weekend
- Schedule variability buffer

  Ideal
- Operational strategy

  Scheduled Departure Time
- Weather

Normal

Table 6-1 Number of Resources on Time Shift

	Period	Number of Resources (Case 1)	Number of Resources (Case 2)
Time Slot 1	00:00 - 06:00	50	50
Time Slot 2	06:00 - 12:00	30	30
Time Slot 3	12:00 - 17:00	50	50
Time Slot 4	17:00 - 00:00	30	50

The number of resources is the only parameter varied in this section. Table 6-1 shows the selected number of resources that is tested. Case 1 has fewer resources than Case 2 in time slot 4. Time slot 2 has a morning rush hour, but it has only 30 resources for both cases. The reason for that is checking the handling ability of the morning rush hour's delay, and how it propagates to the afternoon.

Figure 6-2 shows the departure delay time of each arrival by applying Case 1. It has 30 resources for every activity in the time slot four periods. From early morning to noon, flights departing earlier than scheduled time are observable. (The negative delay time means early departure with respect to the scheduled departure time.) The longest delay time was around five hours corresponding to a flight that arrived around 10 pm.

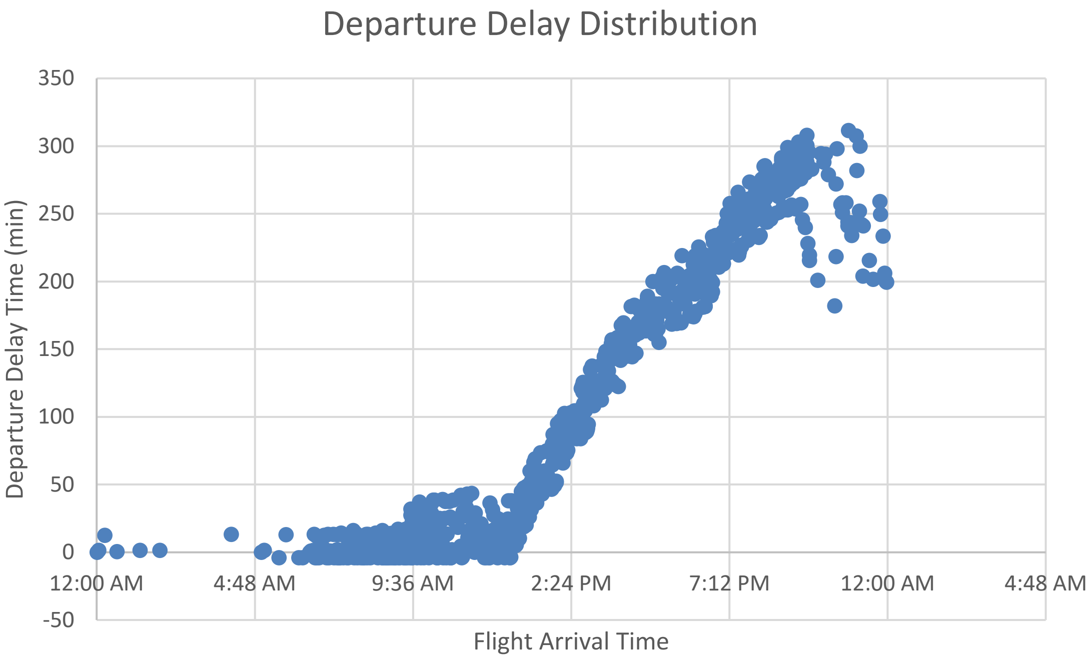


Figure 6-2 Departure Delay Time Distributions (Case 1)

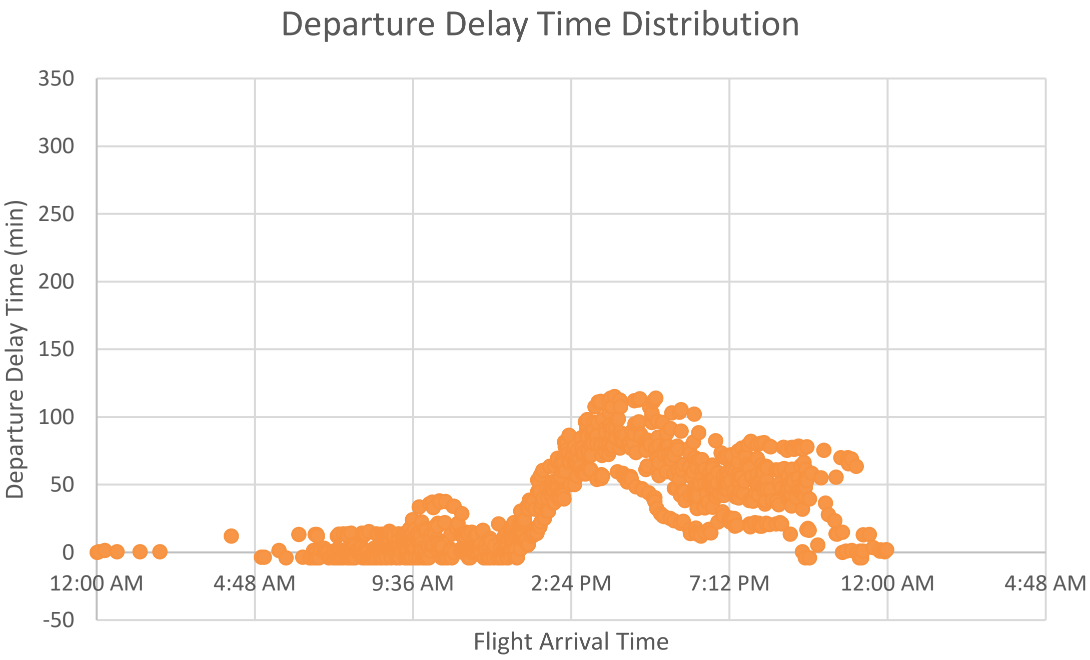


Figure 6-3 Departure Delay Time Distributions (Case 2)

Figure 6-3 shows the departure delay time of each arrival by applying Case 2. It has 50 resources for every activity in the time slot four periods. The flights departing earlier than scheduled time are also observable in this case. The longest delay is around two hours, corresponding to a flight that arrived around 4 pm.

To indicate the specific reason for the delay time, the operation time of each activity is tracked. Figure 6-4 shows the example of flight with the delay time of each activity. It shows the tracked information of all sub-operations: preparation, execution, and post-processing.

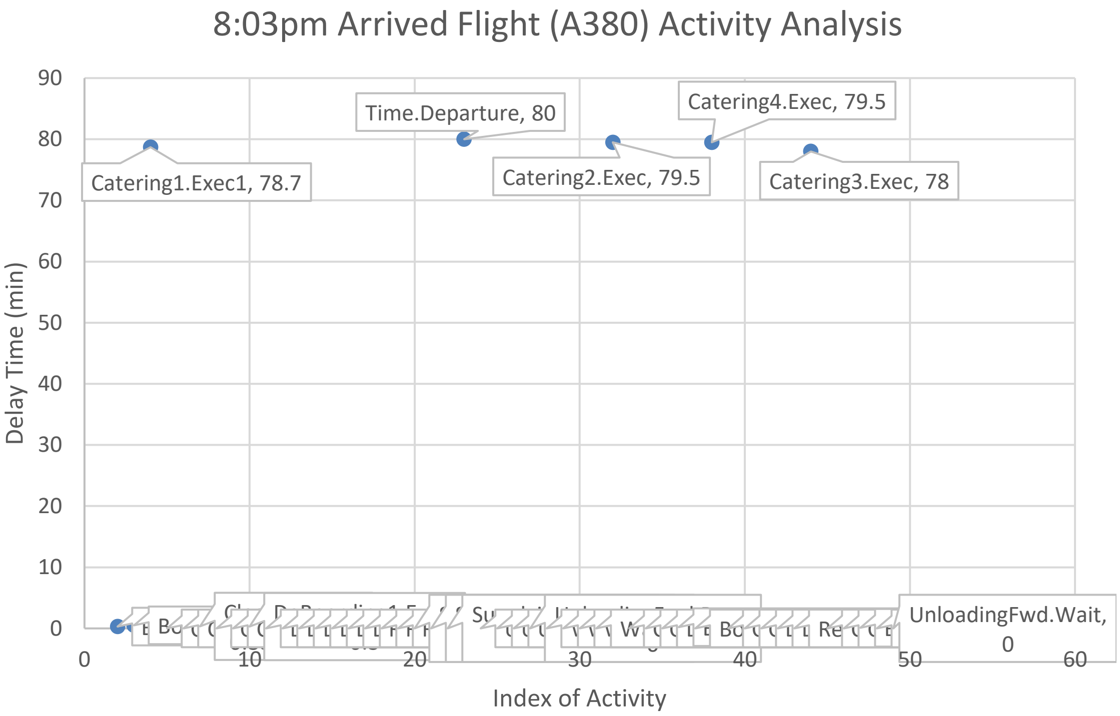


Figure 6-4 Tracked Information of Activity Delay

It is evident that catering execution is a critical factor to contribute to the delay. Since all other processes have the delay time less than ten minutes or zero delay time, the main reason for the delay can be assumed as the execution of the catering.

Catering can take place up to four places in one aircraft. That means a single aircraft can request four resources for catering. Even if catering has the same number of resources as other activities, the actual work is handling up to four catering locations with it. Thus, to estimate the real delay time and find the lower bound for the number of resources, the catering activity would take much more resources than the other activities. Table 6-2 shows the number of resource distribution except catering. The number of resources for catering can be seen in table 6-3.

Table 6-2 Number of Resources for the Activity except Catering

	Period	**Number of Resources (Case 3)**	**Number of Resources (Case 4)**	**Number of Resources (Case 5)**
Time Slot 1	00:00 - 06:00	20	25	30
Time Slot 2	06:00 - 12:00	20	25	30
Time Slot 3	12:00 - 17:00	20	25	30
Time Slot 4	17:00 - 00:00	20	25	30

Table 6-3 Number of Resources for Catering

	Period	**Resources for Catering**
Time Slot 1	00:00 - 06:00	200

Time Slot 2	06:00 - 12:00	100
Time Slot 3	12:00 - 17:00	200
Time Slot 4	17:00 - 00:00	200

Three additional cases (Cases 3, 4, and 5) were analyzed such that the parameters except for the number of resources (Level of congestion, Day, Schedule variability buffer, Operational strategy, and Weather) were the same as with Cases 1 and 2.

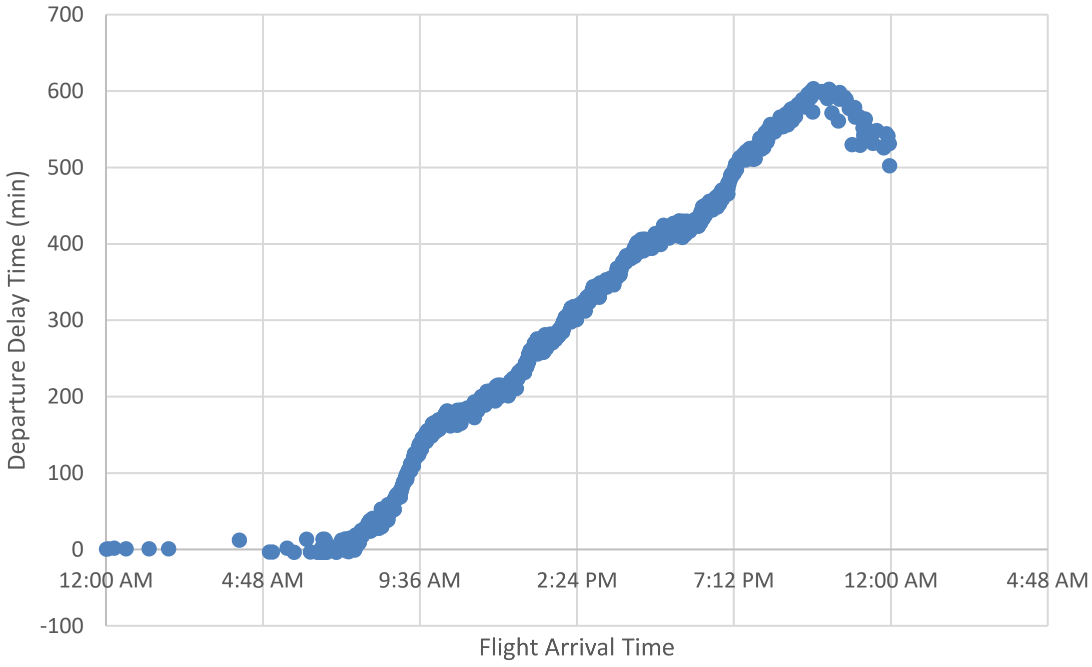


Figure 6-5 Departure Delay Time Distributions (Case 3)

Figure 6-5 shows the departure delay time of each arrival by applying 20 resources. It has 20 resources for every activity all day. The flights that are ready for departure earlier than scheduled time is observable at dawn. The longest delay time was around ten hours, corresponding to the flight that arrives around 10 pm.

This results in an unrealistic delay time of over ten hours due to the insufficiency of the resources, even though the use-case considered is illustrative. Therefore, 20 resources cannot be the lower bound for the number of resources.

Figure 6-6 shows the departure delay time of each arrival by applying 25 resources. It has 25 resources for every activity all day. This case demonstrates flights ready for early departure being observable at dawn and morning. The longest delay time was around five hours corresponding to a flight that arrives around 10 pm.

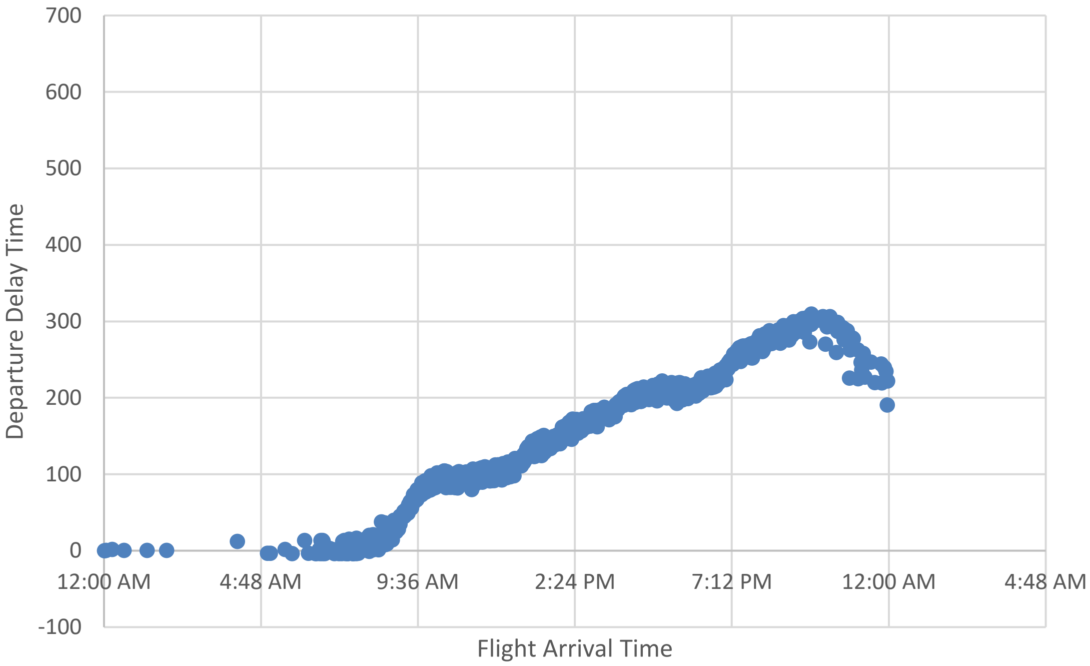


Figure 6-6 Departure Delay Time Distributions (Case 4)

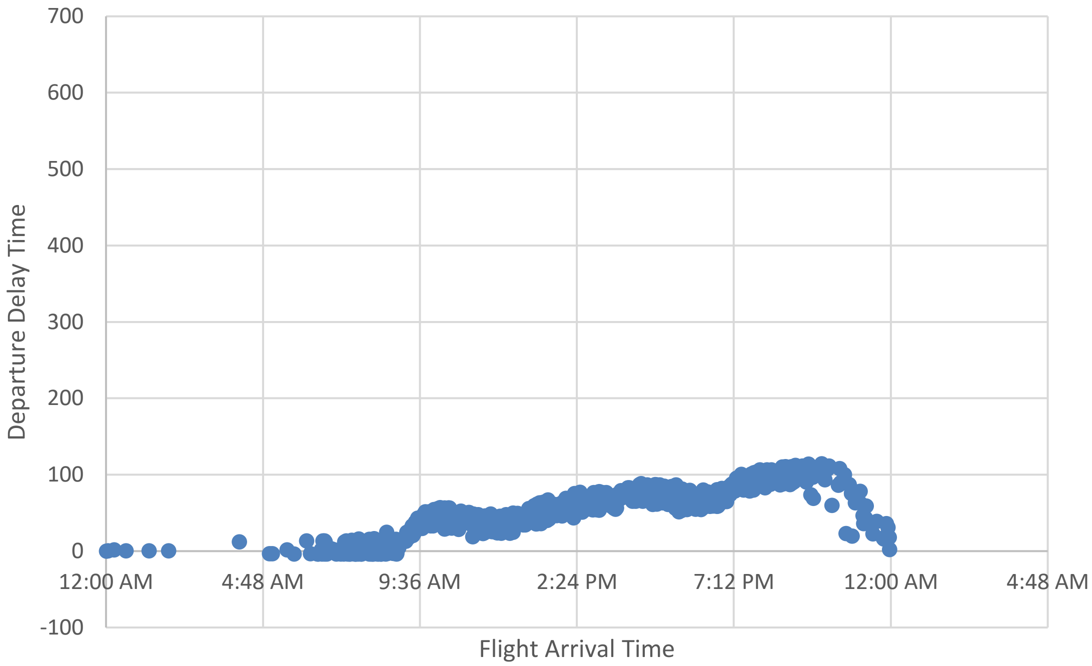


Figure 6-7 Departure Delay Time Distributions (Case 5)

Figure 6-7 shows the departure delay time of each arrival by applying 30 resources. It has 30 resources for every activity all day. Flights that are ready for an on-time departure are observable at dawn and morning. The longest delay time was around two hours corresponding to a flight that arrives around 10 pm.

In comparison with figure 6-6 and 6-7, the longest delay time decreases from five hours to two hours. If the flight is operated in the rush hour under the bad weather condition, waiting two hours is realistic due to too much demand for the impacted resources. Waiting five hours due to the demand is threshold in comparison to the illustrative case of 20 resources. Thus, 30 resources are excluded for the lower bound, and 25 resources are selected to be the lower bound for the number of resources.

In summary, the worst case scenario equals working with 25 resources. The best case works with an unlimited number of resources. The real case shows only the bounded condition. It will be discussed in chapter 7 with the results from the experiments evaluation.

- Best case:

$$\text{Number of resources} = \text{unlimited (infinite)}$$

- Worst case:

$$\text{Number of resources} = 25$$

- Real case:

$$25 < \text{Number of resources} < \text{unlimited}$$

6.2.2 Schedule Variability Buffer

Schedule variability buffer functions as a warning for the unexpected delay factors from the turnaround process and arrival. It is already discussed in section 2.2.3 and 5.4. Thus, detailed information of the variable can be referred in those sections. There are a total of three cases:

- Ideal

$$\text{Schedule variability buffer} = 0$$

- Robust

$$0 < \text{Schedule variability buffer} < \max$$

- Largest

$$\text{Schedule variability buffer} = \text{max}$$

The ideal case has a clear definition, which represents a zero time for the schedule variability buffer. The scenario of the ideal case may be risky in the real world because it represents no preparation for future incidents or unexpected delay factors. However, it can reduce scheduling cost from the airline's perspective. Thus it will be tested in the simulator in the purpose of its impact analysis.

The largest case has an unclear definition, which represents the maximum time of schedule variability buffer. In order to find the maximum value, the early arrival time data from BTS has been referenced. (It can be accessed on BTS's website.)

In terms of the level of congestion, the busy level represents July traffics, and the normal level represents November traffics. Therefore, both months' data is evaluated. As expected, July has a shorter range of early arrival time than November as illustrated in table 6-4.

Table 6-4 Minimum and Maximum of Early Arrival Time

	July	**November**
Minimum	-47	-58
Maximum	-1	-1

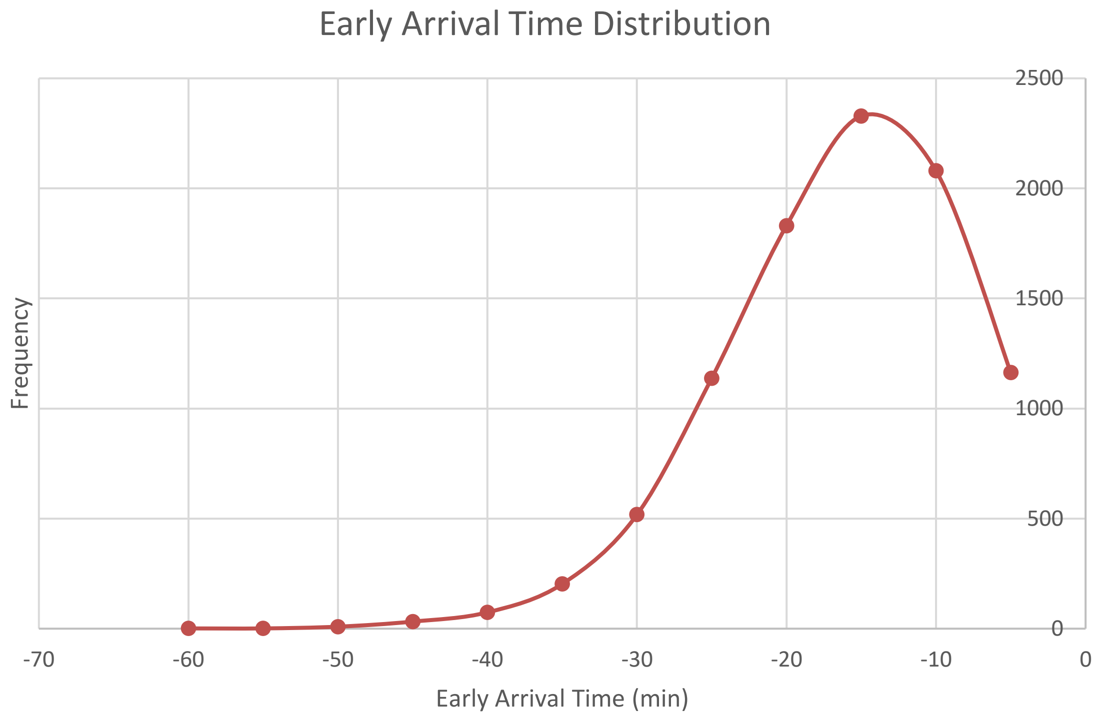


Figure 6-8 Tracked Early Arrival Time Distribution

Figure 6-8 shows the frequency distribution of early arrival time. It consists of all tracked flights with an early arrival on Tuesday and Friday in July and November. The frequency is counted on each bin, which is of equal size as five minutes. It shows a skewed left and unimodal shape. The peak is formed on -15 minutes.

In general, the aircraft, which requires a longer turnaround time, has more potential factors to make delays. It means applying the same schedule variability buffer for all aircraft is not fair. Thus, the longer turnaround aircraft will be modeled as having a longer schedule variability buffer. Likewise, the shorter turnaround aircraft will be assigned shorter schedule variability buffer.

Since the peak has formed on -15 minutes, the shortest turnaround aircraft will take 15 minutes as the largest case of the schedule variability buffer. For the longest turnaround aircraft, 45 minutes buffer is selected because -50, -55 and -60 minutes take only 0.01%, 0.01%, and 0.10 % in the whole distribution respectively. Thus, those three time values are ignored, and -45 minutes are picked.

- Shortest turnaround time of a defined aircraft model
  B737-600, 33 minutes
  - Schedule variability buffer for the largest case
    15 minutes
- Longest turnaround time of defined aircraft model
  A380, 90 minutes
  - Schedule variability buffer for the largest case
    45 minutes

This research assumes that the schedule variability buffer is linearly increased. Thus, using the two data points described above, a linear function is generated as illustrated in figure 6-9. Figure 6-9 shows the largest case of schedule variability buffer for all aircraft models.

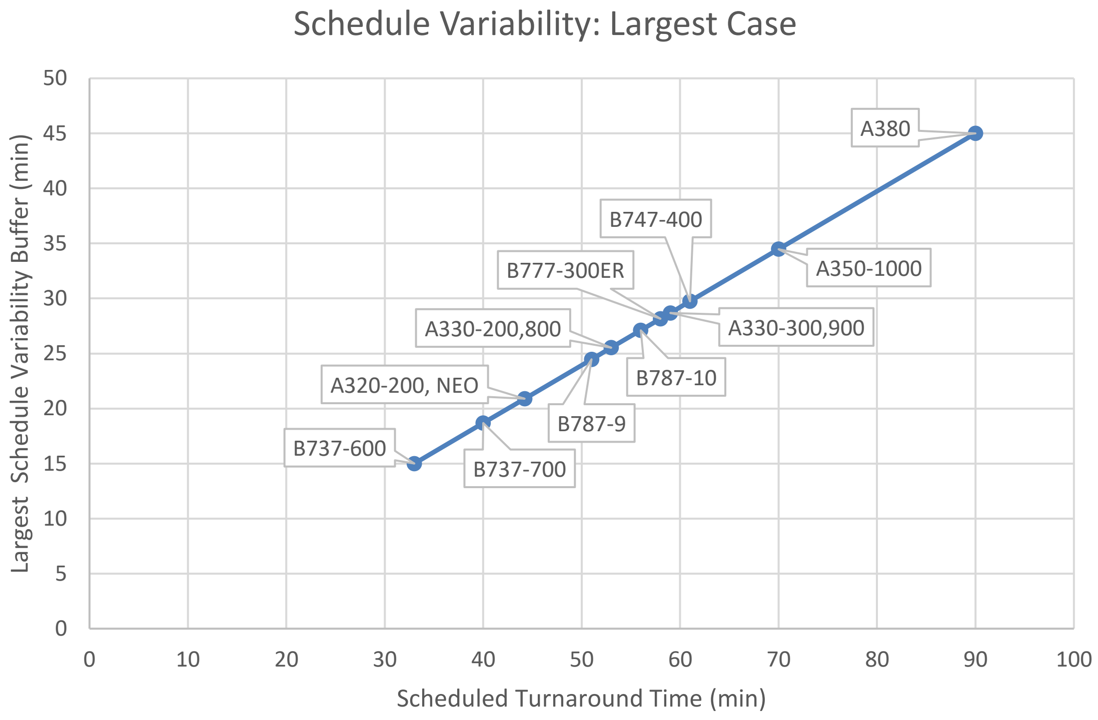


Figure 6-9 Schedule Variability Buffer Time Value for the Largest Case by Aircraft Model

In summary, the ideal case means there is no schedule variability buffer. Thus, there is no buffer in case of an unexpected incident. The largest case has maximum schedule variability buffer to absorb any future delay. To set the maximum schedule variability buffer value, the actual early arrival time distribution is referenced. The robust case has the value between the ideal case and largest case. It will be discussed in chapter 7 with the results from the experimental evaluation.

- Ideal

$$\text{Schedule variability buffer} = 0$$

- Robust

$$\text{Ideal case} < \text{Schedule variability buffer} < \text{Largest case}$$

- Largest

Aircraft Model	Schedule Variability Buffer (min)
B737-600	15
B737-700	18.68
A320-200, NEO	20.89
B787-9	24.47
A330-200,800	25.53
B787-10	27.11
B777-300ER	28.16
A330-300,900	28.68
B747-400	29.74
A350-1000	34.47
A380 main and upper deck	45

6.3 Experiments Evaluation under Nominal Condition

It has been discussed how to implement the simulator and to design the experiments with it in chapter 5 and previous sections in chapter 6. Thus, the primary purpose of this section is the illustration of the results of the experiments. There are four parts by the operational strategies and the weather:

- Operational strategy
  - Schedule departure time (SDT)

    - First-come-first-served (FCFS)
- Weather
    - Nominal
    - Off-nominal

Here, only evaluates the nominal weather scenario, which means there is no consideration of the delay factor due to the bad weather. The ability of the simulator will be evaluated under the nominal condition. The off-nominal condition will be discussed in section 6.4.

It will be discussed that each analysis and their characteristics. Then, it will be announced that their comparison to evaluate the hypotheses in the dissertation.

The FCFS strategy's results work as the baseline that illustrates how it is operated today; then the comparison will proceed. Since SDT has been suggested as a queueing criterion in the hypothesis, the result of the comparison will show approving the hypothesis or not.

6.3.1 *First-Come-First-Served (FCFS)*

Section 6.3.1 consists of the results when the operational strategy takes FCFS (First-Come-First-Served) under nominal weather condition.

6.3.1.1 Busy (Level of Congestion) – Weekday

This part includes the output of the simulation after running it with the FCFS strategy. It applies the busy season's weekday arrival schedule. The output illustrates the departure delay time, the number of delayed flights, and the number of early flight departures.

Figure 6-10 shows the departure delay time of each arrival from the busy season's weekday schedule with the worst case for the resources when the baseline operational strategy is applied. It follows the strategy: First Come First Served. For that case, it is no matter how long the flight before take-off.

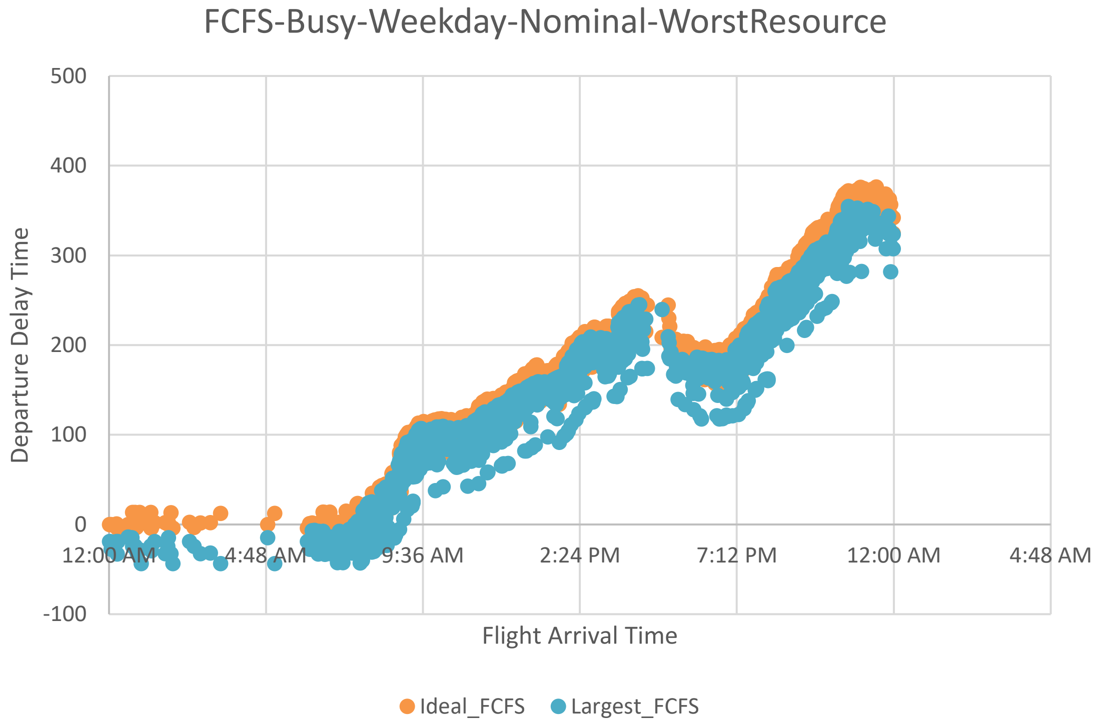


Figure 6-10 Departure Delay Distribution – FCFS, Busy, Weekday, Nominal Weather and Worst Resources

For the resources, it has a total of 25 resources for deboarding, boarding, cleaning, loading, unloading, refueling, supplying water, and waste water activity, and a total of 50 resources for the catering activity.

It has a total of 1103 flights in a day. A total of 983 flights are evaluated as a delayed flight for the ideal case of the schedule variability buffer. For the largest case of the schedule variability buffer, a total of 950 flights are labeled as a delayed flight. The longest delay time is around six hours for the ideal case and largest case; the largest case has slightly shorter than the ideal case. That flight arrived around 11 pm for both cases.

In the plot, two peaks are observable around 4 pm and 11 pm. After 4 pm, it is observed that the departure delay time has a decreasing trend until 7 pm because of the reduced number of flight arrivals. Thus, the system can recover its operation. However, due to the night rush hour, the delay time has an increasing trend again after 7 pm. It proves the system handles too much or affordable demand and its recovery ability when the demand is reducing like realistic system.

Figure 6-11 shows the departure delay time of each arrival by FCFS strategy from the busy season’s weekday schedule with the best case of a number of resources. (The expanded version of figure 6-11 is illustrated in Appendix G.) The weather is assumed as nominal. For the resources, it has an unlimited number of resources for every activity: deboarding, boarding, catering, cleaning, loading, unloading, refueling, supplying water, and waste water activity.

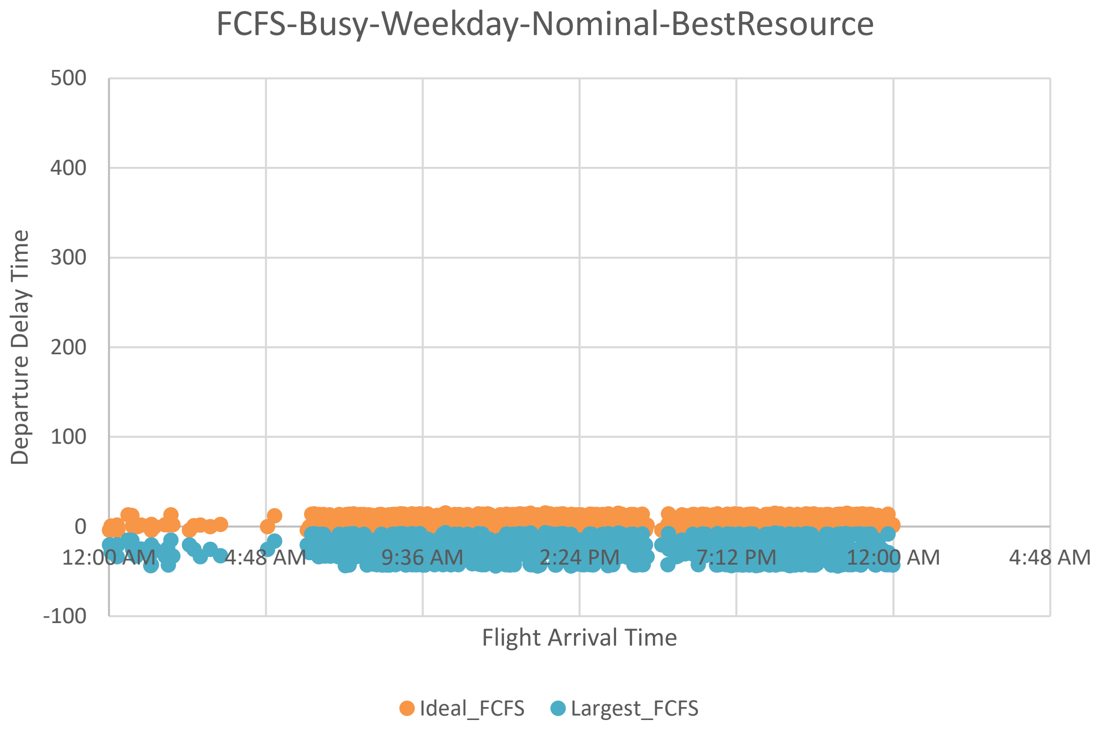


Figure 6-11 Departure Delay Distribution – FCFS, Busy, Weekday, Nominal Weather and Best Resources

For the worst case of the number of resources, it has an increasing trend about the departure delay time. Unlike the worst case, the best case has strip-shaped distribution. Thus, the number of resources has a significant contribution to reducing the departure delay time.

When looking at the difference between the ideal case and the largest case of the schedule variability buffer, the number of early flight departure shows the difference. For the ideal case of the schedule variability buffer, there are a total of three flights from 1103 arrived flights are evaluated as a delayed flight. Furthermore, a total of 219 flights had an earlier departure than their scheduled departure time.

For the largest case of the schedule variability buffer, there is no flight, which identified as a delayed flight. In that case, all 1103 flights had an earlier departure than their scheduled departure time, which means having a negative delay time value.

Table 6-5 includes the number of delayed flights and the number of early flight departure by schedule variability buffer and number of resources scenario.

Table 6-5 Statistics of Busy – Weekday with FCFS Strategy – Nominal Weather

Schedule Variability Buffer	Resources	Delayed Number of Flights	Early Flight Departure
Ideal	Worst	983	21
Ideal	Best	3	219
Largest	Worst	950	132
Largest	Best	0	1103

6.3.1.2 Busy (Level of Congestion) – Weekend

This part figures out the output of the simulation after running it by the FCFS strategy with the busy season's weekend arrival schedule. The output consists of the departure delay time, the number of delayed flights, and the number of early flight departures.

Figure 6-12 shows the departure delay time of each arrival by FCFS strategy from the busy season's weekend schedule. For the resources, it follows the worst case scenario.

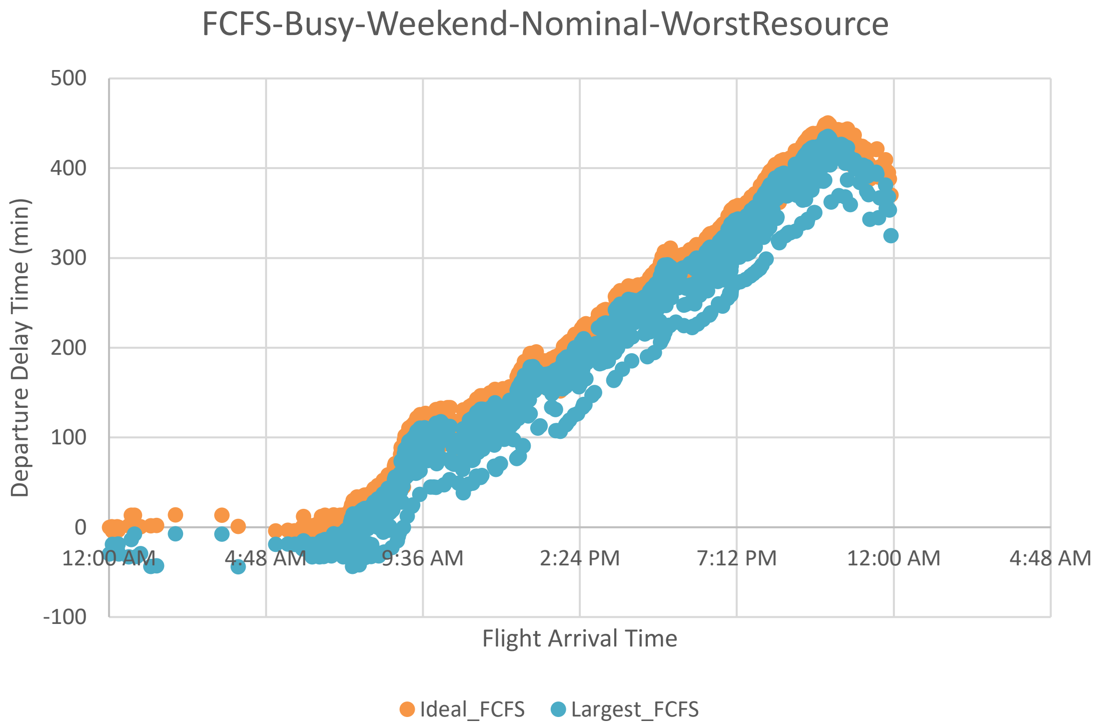


Figure 6-12 Departure Delay Distribution – FCFS, Busy, Weekend, Nominal Weather and Worst Resources

A total of 1028 flights from 1119 flights are identified as a delayed flight when follows the ideal case of the schedule variability buffer. For the largest case of the schedule variability buffer, a total of 975 flights are classified as a delayed flight.

Around 10 pm, one peak is observed in figure 6-12 for both schedule variability buffer cases. The longest delay time is over seven hours for both cases. The busy season with the weekend schedule has the largest number of flights. That is why it has a longer delay time than the weekday schedule.

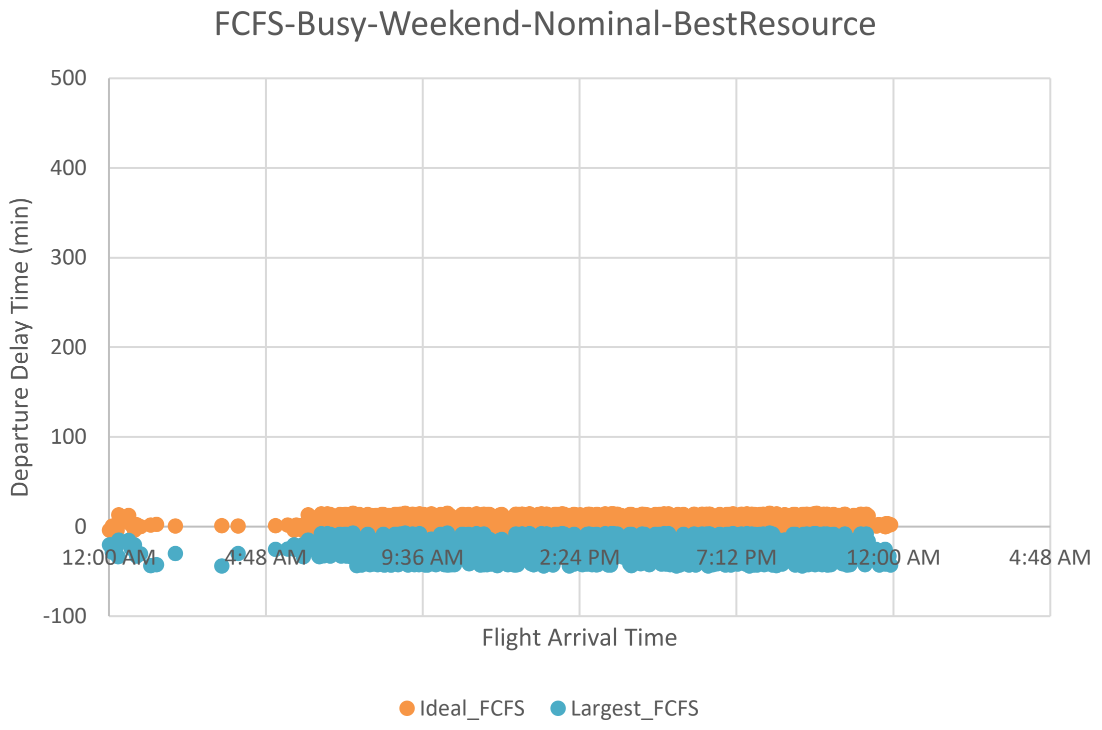


Figure 6-13 Departure Delay Distribution – FCFS, Busy, Weekend, Nominal Weather and Best Resources

Figure 6-13 shows the departure delay time of each arrival by FCFS strategy from the busy season's weekend schedule. (The expanded version of figure 6-13 is illustrated in Appendix G) Since it follows the best case scenario for the resources, it has an unlimited number of resources for every activity: deboarding, boarding, catering, cleaning, loading, unloading, refueling, supplying water, and waste water activity.

Overall, it makes a strip-shaped distribution, not an increasing-shaped. Regarding the shape, it is similar to the weekday case.

When checking the ideal case of the schedule variability buffer, there is only one delayed flight. However, it is delayed 15.3 minutes, which means pretty close to an on-time flight. A total of 221 flights had an earlier departure than their scheduled departure time.

For the largest case of the schedule variability buffer, there is no flight which classified as a delayed flight. In that case, all flights were ready to depart earlier than their scheduled departure time, which means having a negative delay time value.

Table 6-6 includes the number of delayed flights and the number of early flight departures by schedule variability buffer and number of resources scenario.

Table 6-6 Statistics of Busy – Weekend with FCFS Strategy – Nominal Weather

Schedule Variability Buffer	Resources	Delayed Number of Flights	Early Flight Departure
Ideal	Worst	1028	19
Ideal	Best	1	221
Largest	Worst	975	116
Largest	Best	0	1119

6.3.1.3 Normal (Level of Congestion) – Weekday

This part explains the output of the simulation after running it by the FCFS strategy with the normal season's weekday arrival schedule. The output shows the departure delay time, the number of delayed flights, and the number of early flight departures.

Figure 6-14 shows the departure delay time of each arrival by FCFS strategy from the normal season's weekday schedule. For the resources, it takes the worst scenario.

Unlike the busy season, the normal season has less traffics. The number of daily arrival flight is less than one thousand.

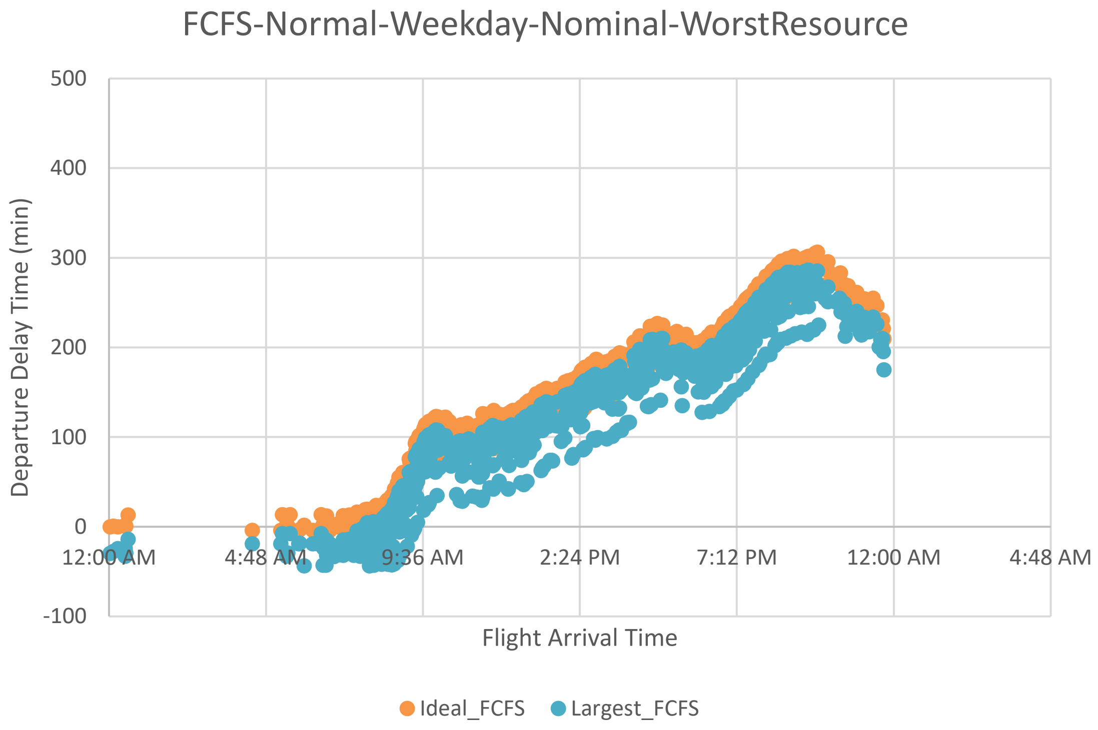


Figure 6-14 Departure Delay Distribution – FCFS, Normal, Weekday, Nominal Weather and Worst Resources

For the ideal case of the schedule variability buffer, there are a total of 846 from 951 flights in a daily schedule, which are classified as a delayed flight. The longest delay time is around five hours. That flight arrived around 10 pm.

For the largest case of the schedule variability buffer, a total of 801 flights are evaluated as a delayed flight. The longest delay time was slightly less than five hours, and that flight arrived around 10 pm. In that case, the schedule variability buffer makes a difference around 15 to 20 minutes for each flight's departure delay time.

Two peaks are observable around 5 pm and 10 pm in figure 6-14. After 5 pm, the departure delay time has a slightly decreasing trend until 6 pm because of the less number of flight arrival. Thus, the system took a recovery period at that time. However, due to the night rush hour, the delay time has an increasing trend again. The ability of recovery is also captured when applying the normal season's schedule.

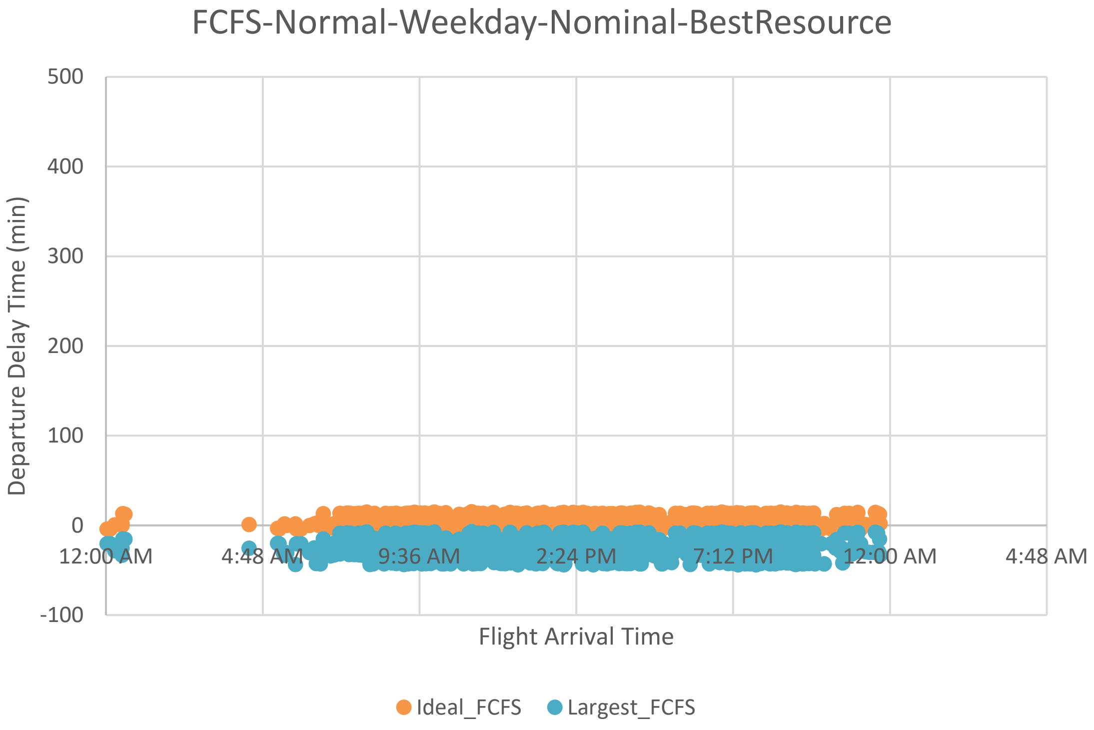


Figure 6-15 Departure Delay Distribution – FCFS, Normal, Weekday, Nominal Weather and Best Resources

Figure 6-15 shows the departure delay time of each arrival by FCFS strategy from the normal season's weekday schedule. It results from the nominal weather condition. For the resources, it follows the best case scenario. Thus it has an unlimited number of resources for every activity. Like the previous figures, the best case has strip-shaped distribution whenever apply the ideal case or the largest case for the schedule variability buffer. Therefore, if there are a million and one resources, the schedule variability buffer barely affects to a flight delay.

The arrival scenario has a total of 951 flights. For the largest case of the schedule variability buffer, no delayed flight is observed. In other words, all flights got on-time performance. In that case, all flights finished their departure preparation before their scheduled departure time, which means having a negative delay time value.

One delayed flight is observed when the ideal case of the schedule variability buffer is applied. However, that flight has 15.3 minutes delay. It just exceeds 0.3 minutes to on-time performance. In terms of the early flight departure, a total of 195 flights had an early departure with respect to their scheduled departure time.

Table 6-7 includes the number of delayed flights and the number of early flight departures by schedule variability buffer and number of resources scenario.

Table 6-7 Statistics of Normal – Weekday with FCFS Strategy – Nominal Weather

Schedule Variability Buffer	Resources	Delayed Number of Flights	Early Flight Departure
Ideal	Worst	846	17
Ideal	Best	1	195
Largest	Worst	801	124
Largest	Best	0	951

6.3.1.4 Normal (Level of Congestion) – Weekend

This part specifies the output of the simulation after running it by the FCFS strategy with the normal season's weekend arrival schedule. The output represents the departure delay time, the number of delayed flights, and the number of early flight departures.

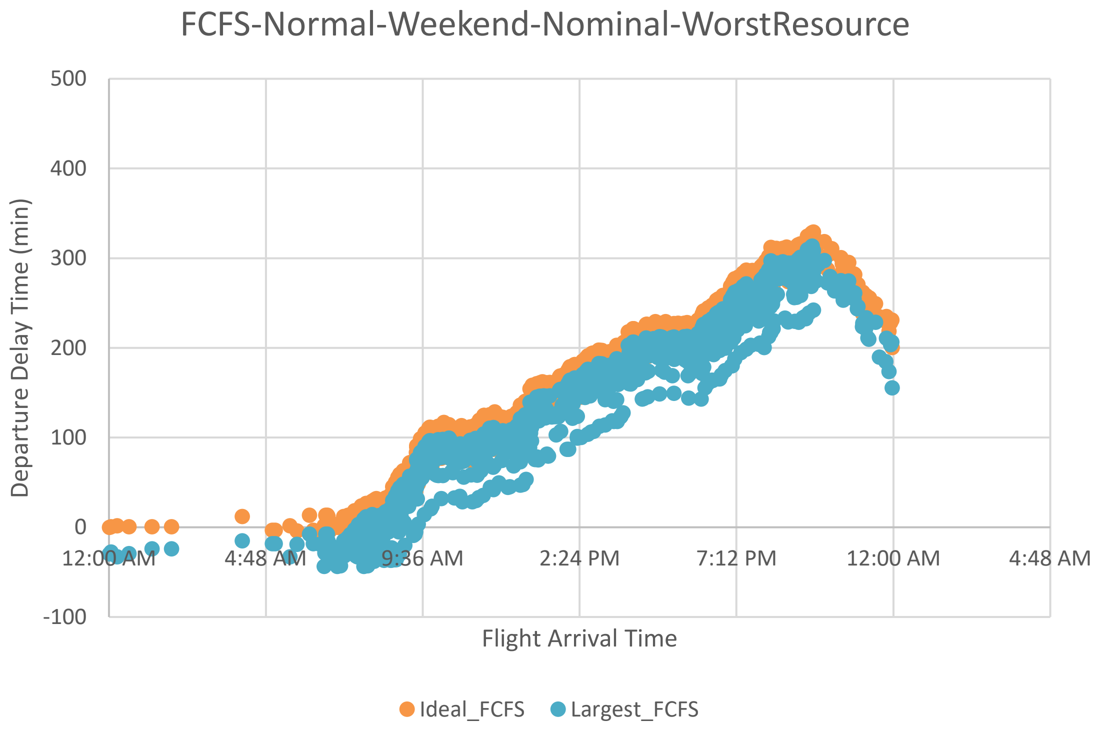


Figure 6-16 Departure Delay Distribution – FCFS, Normal, Weekend, Nominal Weather and Worst Resources

Figure 6-16 shows the departure delay time of each arrival by FCFS strategy from the normal season's weekend schedule. It follows the worst case's scenario for the number of resources.

The longest delay time is captured around 9 pm. It is about five and a half hours for the ideal case of the schedule variability buffer. The ideal case produces a total of 880 flights which are identified as a delayed flight. For the largest case of the schedule variability buffer, a total of 820 flights are recorded as a delayed flight. The longest delay time is around five hours. It also occurred at around 9 pm.

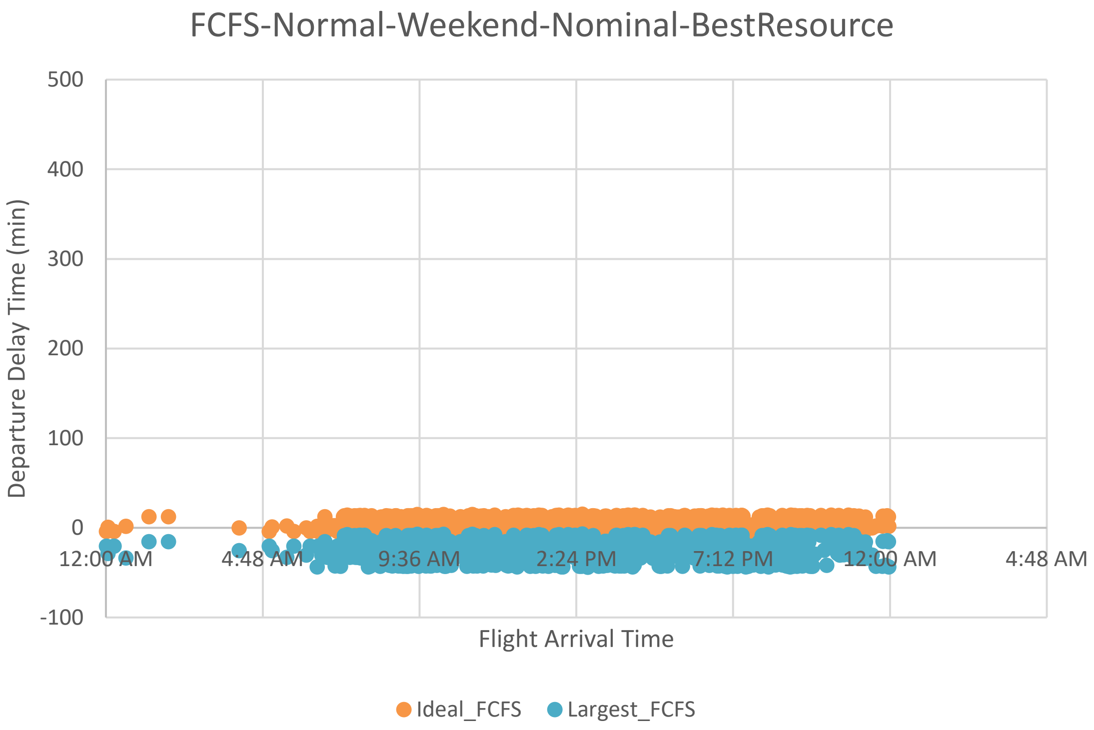


Figure 6-17 Departure Delay Distribution – FCFS, Normal, Weekend, Nominal Weather and Best Resources

Figure 6-17 shows the departure delay time of each arrival by FCFS strategy from the normal season's weekend schedule. For the resources, it follows the best case's scenario. Thus, it has an unlimited number of resources for all activity: deboarding, boarding, catering, cleaning, loading, unloading, refueling, supplying water, and waste water.

The entire arrival schedule has a similar shape when it operates with the best case of the resources. With the naked eye, most of flight delay time are distributed close to the x-axis. For the ideal case of the schedule variability buffer, only one flight is labeled as a delayed flight. Furthermore, a total of 198 flights had early departure than their scheduled departure time. For the largest case of the schedule variability buffer, there is no flight, which classified as a delayed flight. Thus, all 967 arrived flights finished all ground activities earlier than their scheduled departure time and made an early departure.

Table 6-8 includes the number of delayed flights and the number of early flight departures by schedule variability buffer and number of resources scenario.

Table 6-8 Statistics of Normal – Weekend with FCFS Strategy – Nominal Weather

Schedule Variability Buffer	Resources	Delayed Number of Flights	Early Flight Departure
Ideal	Worst	880	10
Ideal	Best	1	198
Largest	Worst	820	114
Largest	Best	0	967

6.3.1.5 Conclusion

Tables 6-9 and 6-10 show the results of the simulator when running the operational strategy ‘FCFS (First-Come-First-Served)’ under the nominal weather condition. Table 6-9 represents the results of the busy season, and table 6-10 represents the results of the normal season.

Table 6-9 Performance of Simulator: Busy season (FCFS under Nominal Weather)

Flight Arrival	Scenario		Delayed flight	Early Departure	Delay Ratios (%)	Longest delay time (min)
1103 (Weekday)	Resource	Worst	983	21	89.12	376.3
	Buffer	Ideal				
	Resource	Worst	950	132	86.12	354.5
	Buffer	Largest				
	Resource	Best	3	219	0.272	15.3
	Buffer	Ideal				
	Resource	Best	0	1103	0	No Delay
	Buffer	Largest				
1119 (Weekend)	Resource	Worst	1028	19	91.86	450.5
	Buffer	Ideal				
	Resource	Worst	975	116	87.13	435.5
	Buffer	Largest				
	Resource	Best	1	221	0.089	15
	Buffer	Ideal				
	Resource	Best	0	1119	0	No Delay
	Buffer	Largest				

Table 6-10 Performance of Simulator: Normal season (FCFS under Nominal Weather)

Flight Arrival	**Scenario**		**Delayed flight**	**Early Departure**	**Delay Ratios (%)**	**Longest delay time (min)**
951 (Weekday)	Resource	Worst	846	17	88.95	306.3
	Buffer	Ideal				
	Resource	Worst	801	124	84.22	286.5
	Buffer	Largest				
	Resource	Best	1	195	0.105	15.3
	Buffer	Ideal				
	Resource	Best	0	951	0	No Delay
	Buffer	Largest				
967 (Weekend)	Resource	Worst	880	10	91	329.3
	Buffer	Ideal				
	Resource	Worst	820	114	84.79	313.5
	Buffer	Largest				
	Resource	Best	1	198	0.103	15.3
	Buffer	Ideal				
	Resource	Best	0	967	0	No Delay
	Buffer	Largest				

When compared (table 6-9), there is more than an one hour difference in the results of the weekday and weekends. The weekend has 16 more flights, but the longest delay time is about 80 minutes longer. The behavior thus shows a butterfly effect, implying that the system is highly sensitive when there is a limited number of resources.

When it follows the best scenario for the number of resources, there are under 1% delayed flight or no delayed flight regardless of the schedule variability buffer. It means that if there are sufficient number of resources, the operational strategy has barely an effect on the delay because it does not require an efficient resource assignment.

When it follows the worst case of a number of resources, there are over almost 85% delayed flight regardless of the schedule variability buffer. It cannot be accepted in the real world, but it is important to bear in mind that the system operated with 25 resources.

Even though the limited condition of resources and busy schedule, the simulator shows its recovery ability and reports each activity’s status by obeying the critical path. Thus, the realization of the integrated aircraft turnaround process through Discrete Event Simulation (DES) is successful. It can handle the arrived flights and allocate the resources based on their demand time regardless of the airline chosen.

Therefore, DES has enabled the realization of the integration of the aircraft turnaround process with the order-based operation. If DES can show a success of scheduled departure time-based operation, then it will substantiate the hypothesis 3:

Hypothesis 3

DES (Discrete Event Simulation) can realize the integration of the aircraft turnaround process.

6.3.2 Schedule Departure Time (SDT)

Section 6.3.2 consists of the results when the operational strategy takes SDT (Schedule Departure Time) under nominal weather conditions.

6.3.2.1 <u>Busy (Level of Congestion) – Weekday</u>

This part consists of the output of the simulation after running it with busy season's weekday arrival schedule when applying the SDT strategy. The output illustrates basically the departure delay time, the number of delayed flights, and the number of early flight departures.

Figure 6-18 shows the departure delay time of each arrival by SDT strategy with the worst case for the resources. For the resources, it has a total of 25 resources for deboarding, boarding, cleaning, loading, unloading, refueling, supplying water, and waste water activity, and a total of 50 resources for the catering activity.

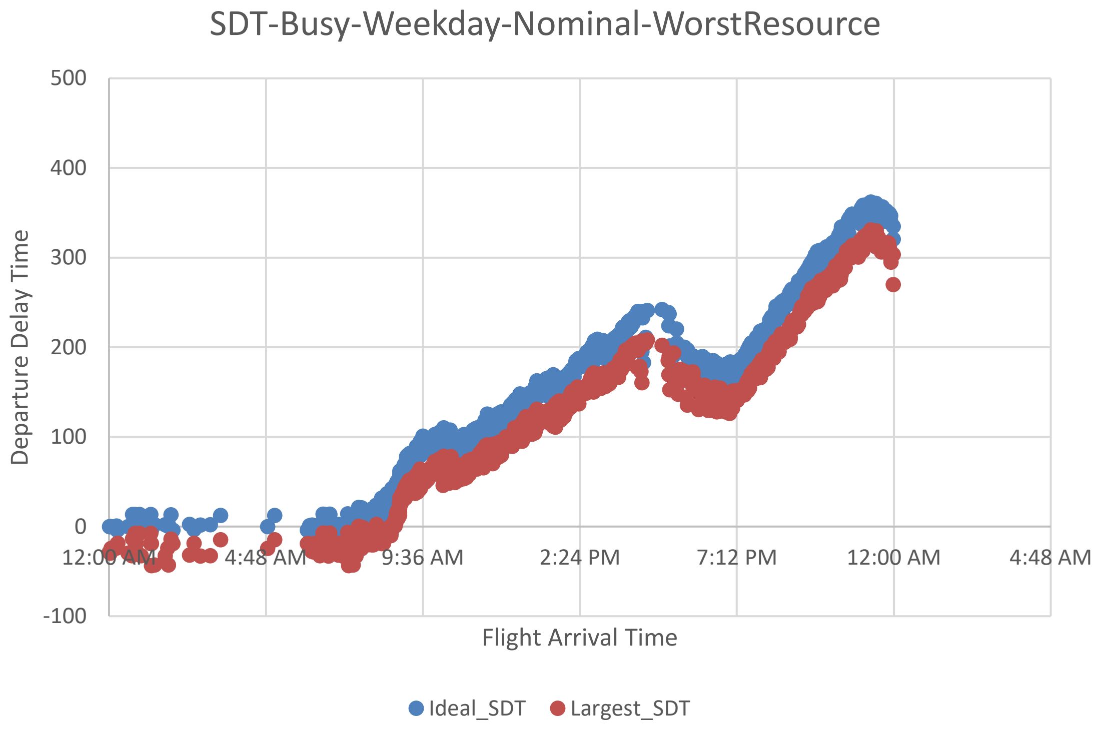


Figure 6-18 Departure Delay Distribution – SDT, Busy, Weekday, Nominal Weather and Worst Resources

The simulation has a total of 1103 flights for the busy season's weekday schedule. A total of 968 flights are evaluated as a delayed flight for the ideal case of the schedule variability buffer. For the largest case of the schedule variability buffer, a total of 913 flights are identified as a delayed flight. The longest delay time is around six hours for the ideal case and five and a half hours for the largest case. That flight arrived around 11 pm for both cases.

The system's recovery ability can be seen in the figure. After 5 pm, the departure delay time has a decreasing trend until 7 pm because of the reduced number of flight arrivals. However, due to the night rush hour, the delay time has an increasing trend again after 7 pm. It has an increasing trend until 11 pm. The delay time hits the peak and decreases again.

Table 6-11 includes the number of delayed flights and the number of early flight departures by schedule variability buffer and number of resources scenario. The best case of the resources shows identical results with the result of the FCFS strategy. The full departure delay distribution of best case is illustrated in Appendix G.

Table 6-11 Statistics of Busy – Weekday with SDT Strategy – Nominal Weather

Schedule Variability Buffer	Resources	Delayed Number of Flights	Early Flight Departure
Ideal	Worst	968	43
Ideal	Best	3	219
Largest	Worst	913	172
Largest	Best	0	1103

6.3.2.2 Busy (Level of Congestion) – Weekend

This part includes the output of the simulation after running it with a busy season's weekend arrival schedule when applying the SDT strategy. The output contains basically the departure delay time, the number of delayed flights, and the number of early flight departures.

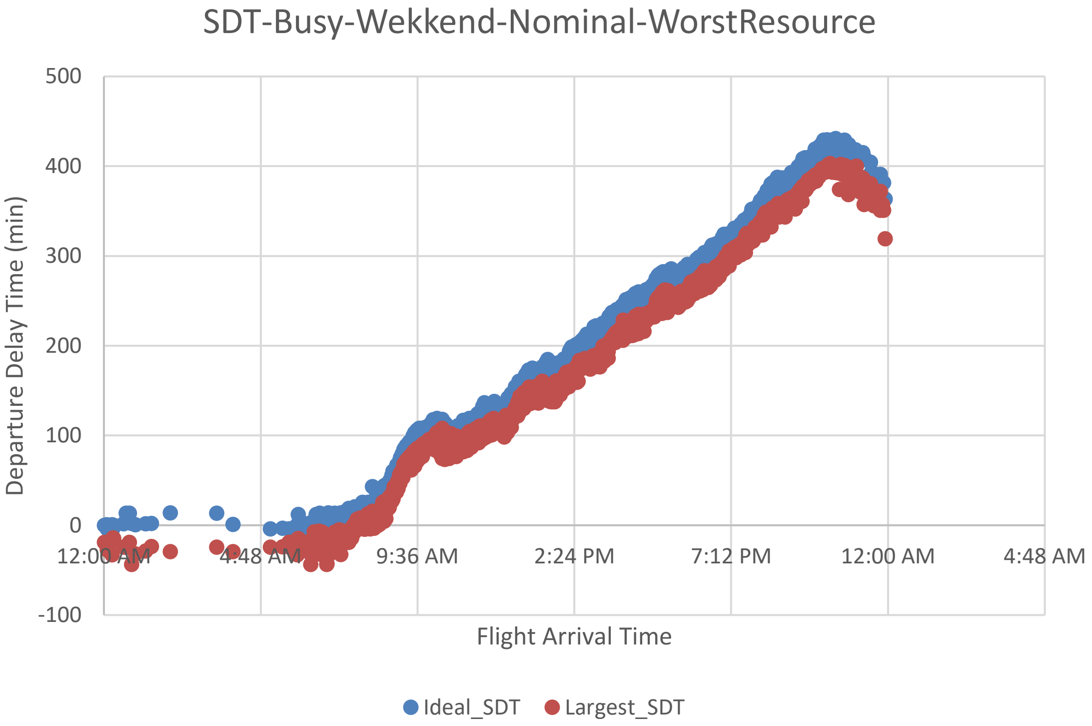


Figure 6-19 Departure Delay Distribution – SDT, Busy, Weekend, Nominal Weather and Worst Resources

Figure 6-19 shows the departure delay time of each arrival by SDT strategy with the worst case for the resources. It illustrates one peak around 10 pm regardless of the schedule variability buffer. The longest delay time is around seven hours for the ideal case and around six and a half hours for the largest case. Since this case represents the busy season with weekend schedule, which means to handle the heaviest traffics, it has a longer delay time than the previous: Busy season.

Table 6-12 includes the number of delayed flights and the number of early flight departures by schedule variability buffer and number of resources scenario. It has total 1119 flights in a day. A total of 1014 flights are identified as a delayed flight for the ideal case of the schedule variability buffer. For the largest case of the schedule variability buffer, a total of 958 flights are labeled as a delayed flight.

The best case of the resources shows identical results with the result of the FCFS strategy. The detailed departure delay distribution of best case is illustrated in Appendix G.

Table 6-12 Statistics of Busy – Weekend with SDT Strategy – Nominal Weather

Schedule Variability Buffer	Resources	Delayed Number of Flights	Early Flight Departure
Ideal	Worst	1014	30
Ideal	Best	1	221
Largest	Worst	958	114
Largest	Best	0	1119

6.3.2.3 Normal (Level of Congestion) – Weekday

This part discusses the output of the simulation after running it with a normal season's weekday arrival schedule when applying the SDT strategy. The output represents the departure delay time, the number of delayed flights, and the number of early flight departures.

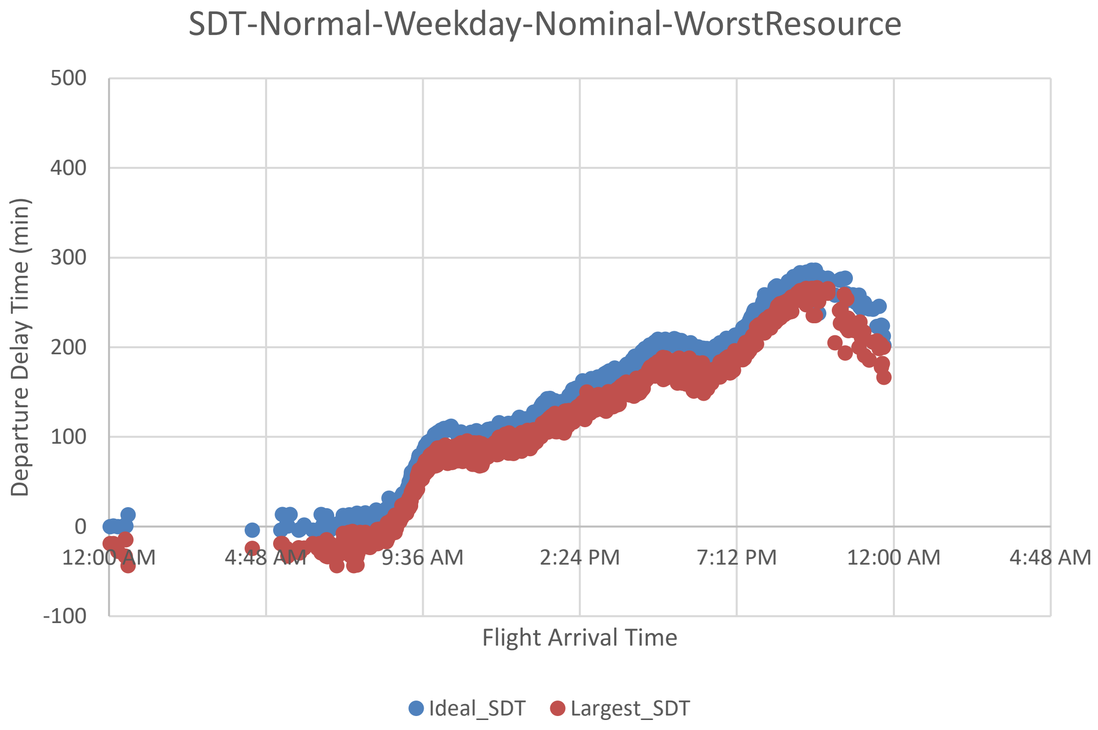


Figure 6-20 Departure Delay Distribution – SDT, Normal, Weekday, Nominal Weather and Worst Resources

Figure 6-20 shows the departure delay time of each arrival by SDT strategy. On the figure, a steep growth is observable in the morning time. Due to the impact of the rush hour traffic, the afternoon traffics are also delayed. It shows proof of the impact of the initial delay. After 5 pm, the departure delay time has a slightly decreasing trend until 6 pm because of the reduced number of flight arrivals. In other words, the system can recover in that period. However, due to the night rush hour, the delay time has an increasing trend again.

Overall, due to the least number of flight arrivals, it has a shorter delay time when compared with the busy season’s cases. The results show a total of 951 flights in a day. A total of 829 flights are classified as a delayed flight for the ideal case of the schedule variability buffer. The longest delay time is around four and a half hours. That flight arrived around 10 pm. For the largest case of the schedule variability buffer, a total of 796 flights are identified as a delayed flight. The longest delay time was around four hours, and that flight arrived around 10 pm.

Table 6-13 includes the number of delayed flights and the number of early flight departures by schedule variability buffer and number of resources scenario. The best case of the resources shows identical results with the result of the FCFS strategy. The full departure delay distribution of best case is illustrated in Appendix G.

Table 6-13 Statistics of Normal – Weekday with SDT Strategy – Nominal Weather

Schedule Variability Buffer	Resources	Delayed Number of Flights	Early Flight Departure
Ideal	Worst	829	40
Ideal	Best	1	195
Largest	Worst	796	123
Largest	Best	0	951

6.3.2.4 Normal (Level of Congestion) – Weekend

This part shows the output of the simulation after running it with normal season's weekend arrival schedule by SDT operational strategy. The output illustrates the departure delay time, the number of delayed flights, and the number of early flight departures.

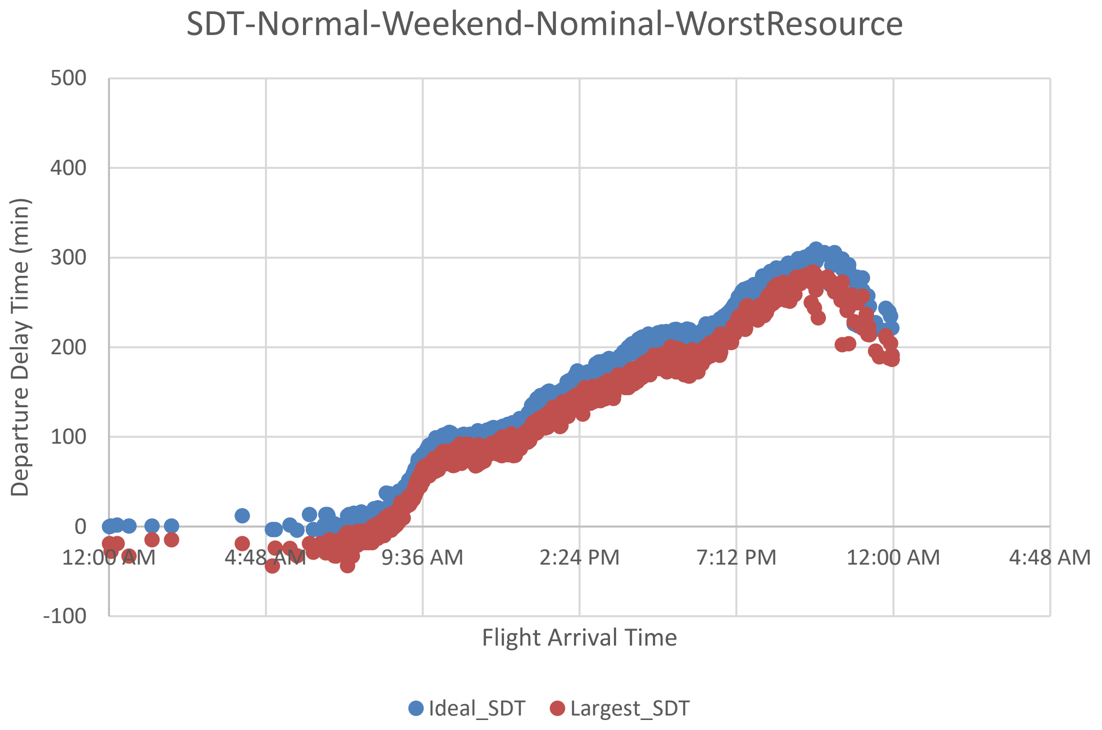


Figure 6-21 Departure Delay Distribution – SDT, Normal, Weekend, Nominal Weather and Worst Resources

Figure 6-21 shows the departure delay time of each arrival from the normal season's weekend schedule. For the resources, it follows the worst case's scenario.

It has more traffic with respect to the normal season's weekday. Thus, the longest delay time is around five hours for the ideal case of schedule variability buffer, and that flight arrived around 11 pm. For the largest case of the schedule variability buffer, the longest delay time is around four and a half hours.

Table 6-14 includes the number of delayed flights and the number of early flight departures by schedule variability buffer and number of resources scenario. The best case of the resources shows identical results with the result of the FCFS strategy. The full departure delay distribution of best case is illustrated in Appendix G

Table 6-14 Statistics of Normal – Weekday with SDT Strategy – Nominal Weather

Schedule Variability Buffer	Resources	Delayed Number of Flights	Early Flight Departure
Ideal	Worst	859	29
Ideal	Best	1	198
Largest	Worst	816	110
Largest	Best	0	967

6.3.2.5 Conclusion

Tables 6-15 and 6-16 show the results of the simulator when running it with the ‘SDT (Scheduled Departure Time)’ operational strategy under the nominal weather condition. Table 6-15 shows the busy season, and table 6-16 shows the normal season.

Table 6-15 Performance of Simulator: Busy season (SDT under Nominal Weather)

Flight Arrival	Scenario		Delayed flight	Early Departure	Delay Ratios (%)	Longest delay time (min)
1103 (Weekday)	Resource	Worst	968	43	87.76	362
	Buffer	Ideal				
	Resource	Worst	913	172	82.77	331
	Buffer	Largest				
	Resource	Best	3	219	0.272	15.3
	Buffer	Ideal				
	Resource	Best	0	1103	0	No Delay
	Buffer	Largest				
1119 (Weekend)	Resource	Worst	1014	30	90.61	431
	Buffer	Ideal				
	Resource	Worst	958	114	85.61	402
	Buffer	Largest				
	Resource	Best	1	221	0.089	15
	Buffer	Ideal				
	Resource	Best	0	1119	0	No Delay
	Buffer	Largest				

Table 6-16 Performance of Simulator: Normal season (SDT under Nominal Weather)

Flight Arrival	Scenario		Delayed flight	Early Departure	Delay Ratios (%)	Longest delay time (min)
951 (Weekday)	Resource	Worst	829	40	87.17	288
	Buffer	Ideal				
	Resource	Worst	796	123	83.70	266
	Buffer	Largest				
	Resource	Best	1	195	0.105	15.3
	Buffer	Ideal				
	Resource	Best	0	951	0	No Delay
	Buffer	Largest				
967 (Weekend)	Resource	Worst	859	29	88.83	309
	Buffer	Ideal				
	Resource	Worst	816	110	84.38	283
	Buffer	Largest				
	Resource	Best	1	198	0.103	15.3
	Buffer	Ideal				
	Resource	Best	0	967	0	No Delay
	Buffer	Largest				

For the worst case of number of resources, there are over 80% delayed flight regardless of the schedule variability buffer. When comparing the result of weekday and weekend, the difference of the longest delay time is more than one hour in the extreme condition of a number of resources. The weekend handles 16 fights more, but the impact of that appears extreme. Therefore, under the insufficient number of resources, handling minor increases to traffic causes unexpected delays.

Furthermore, if the number of resources follows the best case, there are under 1% delayed flight or no delayed flight regardless of the schedule variability buffer.

If the simulation run with the largest schedule variability buffer under the best case of a number of resources, all flights are prepared for their take-off before their scheduled departure time. Even if running with the ideal schedule variability buffer under the best case of a number of resources, around 20% flights are prepared their take-off before their scheduled departure time.

In terms of the schedule variability buffer, the largest case has less delay time than the ideal case. On the whole, it shortens the delay time of each arrival for about 30 minutes. Therefore, it proves that the schedule variability buffer works appropriately.

When applying the SDT strategy, the simulator captures each activity's status through the critical path and shows the resource allocation ability by the entered take-off time. In addition, it proves the proper role of the schedule variability buffer as a buffer time.

It is possible to manage the flight arrivals through the integrated aircraft turnaround process, so DES realizes this integration.

Hypothesis 3 proposes that realization of the integrated aircraft turnaround process through Discrete Event Simulation (DES).

Hypothesis 3

DES (Discrete Event Simulation) can realize the integration of the aircraft turnaround process.

As mentioned in section 5.3, the framework has been developed the DES through the core simulation object, which is composed of the objects: Queue, ResourceManager, and a Scheduler. It can make a decision based on the queueing priority and manage all flights and all resources regardless of the airline chosen. Therefore, DES has enable the successful realization of the integration of the aircraft turnaround process. Thus, hypothesis 3 has been substantiated.

6.3.3 Comparison of Operational Strategy under the Nominal Scenarios

Section 6.3.1 and 6.3.2 introduced the performance of the simulator and evaluated it through the experiments. They illustrate the delay time of departure for each arrival, the number of delayed flights, and the number of early flight departures. The extracted output shows the pattern of delay and the point of the longest delay time. The performance of the simulator proves that the realization of the integrated approach is possible through the DES methodology.

Thus, this section focuses on the comparison of the performance of the operational strategy: SDT and FCFS. To find a better strategy, the comparison will proceed under the worst case of the resources. Since the best case of the resources has shown the same performance regardless of the operational strategy, it is excluded here.

Figure 6-22, 6-23, 6-24, and 6-25 show the departure delay distribution with SDT strategy and FCFS strategy under the nominal weather condition.

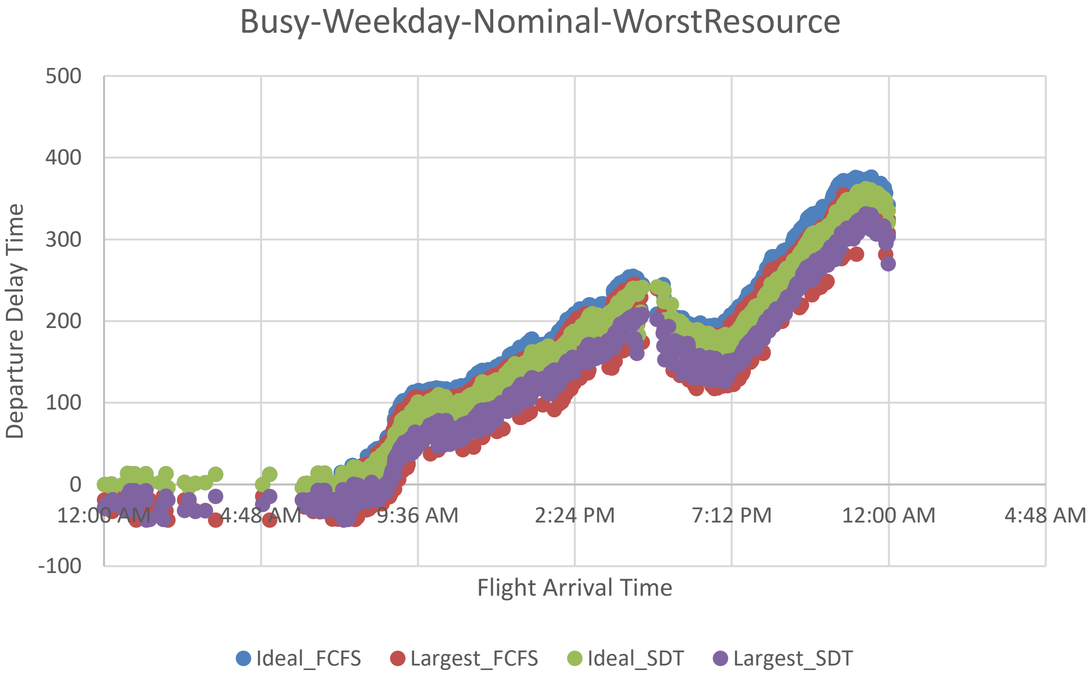


Figure 6-22 Departure Delay Distribution – Busy, Weekday, and Nominal Weather

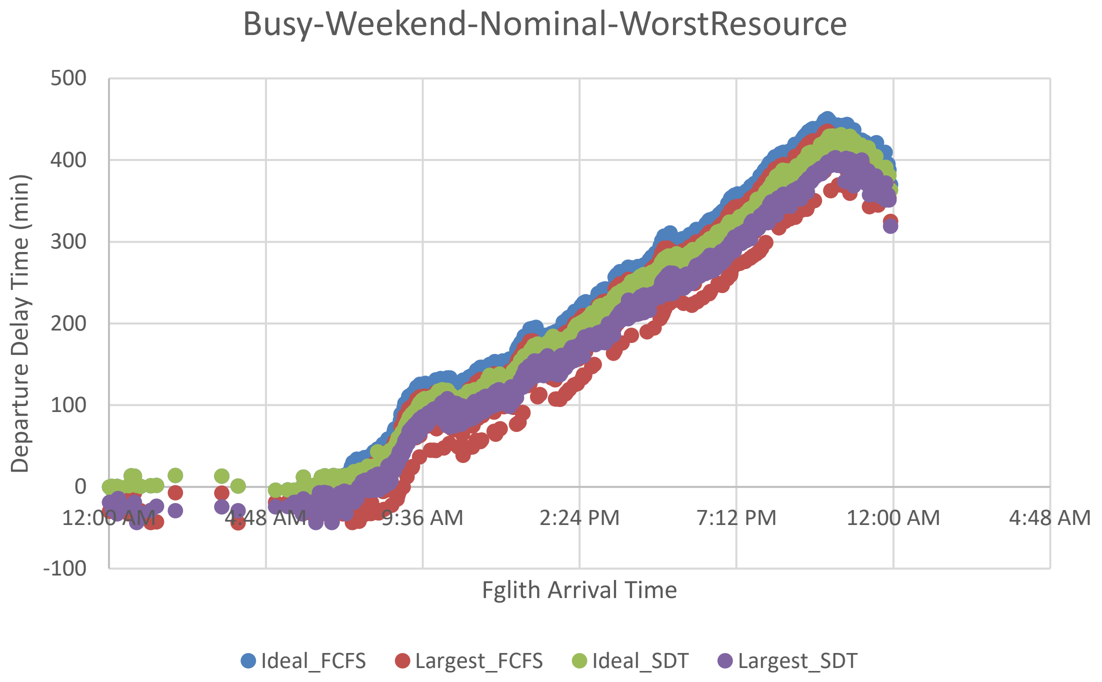


Figure 6-23 Departure Delay Distribution – Busy, Weekend, and Nominal Weather

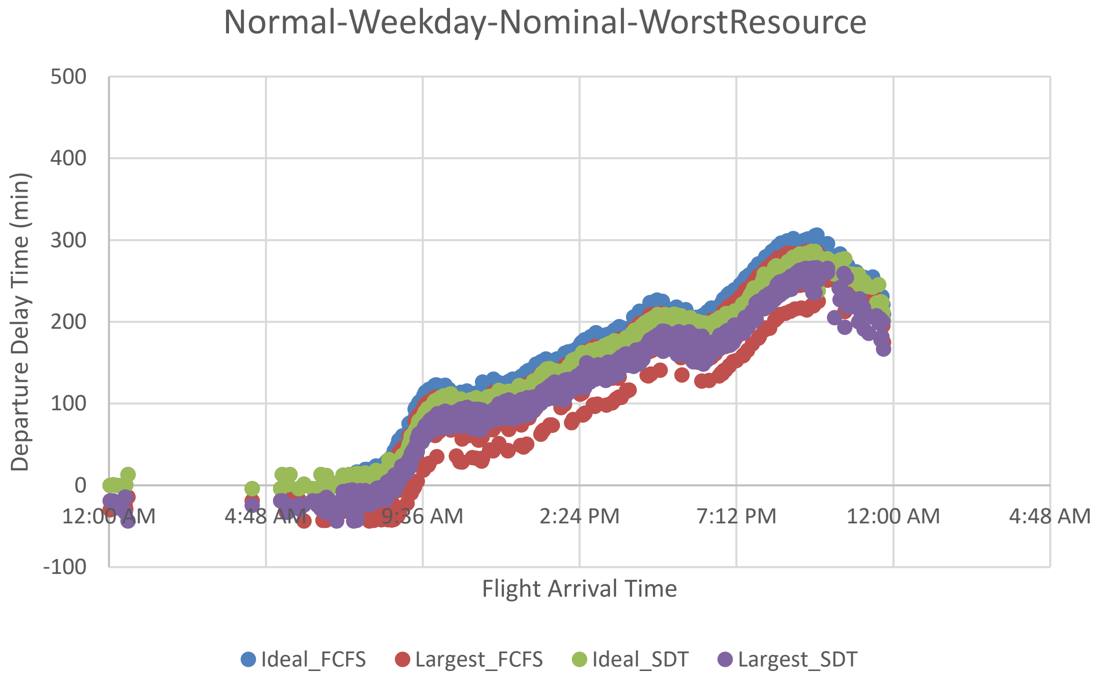


Figure 6-24 Departure Delay Distribution – Normal, Weekday, and Nominal Weather

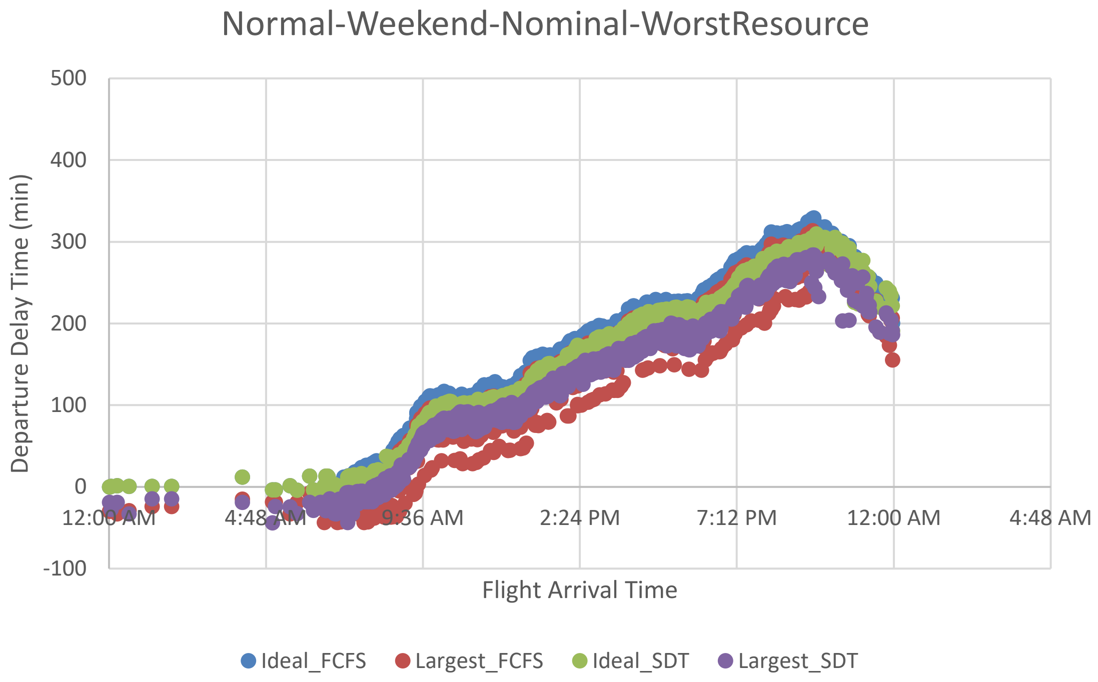


Figure 6-25 Departure Delay Distribution – Normal, Weekend, and Nominal Weather

The spread of the curve is a distinct feature when it compares both strategies: FCFS tend to vary wider than SDT due to the demand-based handling. Overall, the trend of SDT is in agreement with the trend of FCFS if loading the same arrival schedule. The system can hardly be free from the crowded time such as morning and afternoon rush hour when there is an only insufficient number of resources to handle the traffics.

Figures illustrate that the results of SDT are located inside the region of the results of FCFS. Thus, the departure delay distribution with both strategy implicates that FCFS has a longer delay than SDT in general. However, due to the significant overlaps in the plots, it is hard to draw meaningful conclusions from the plots. Thus, the comparison would be continued with the numerical results.

Table 6-17 Number of Delayed Flights by Operational Strategy: Nominal Weather

Flight Arrival	Ideal_ FCFS	Ideal_ SDT	Largest_ FCFS	Largest_ SDT	Resources
Busy-Weekday	983	968	950	913	Worst
Bust-Weekend	1028	1014	975	958	Worst
Normal-Weekday	846	829	801	796	Worst
Normal-Weekend	880	859	820	816	Worst

Table 6-17 shows the number of delayed flights by operational strategy. The highlighted column means showing less number of delayed flights. No matter the schedule variability buffer, SDT demonstrates a better performance than FCFS in terms of the number of delayed flights.

However, the number of delayed flights is not the only metric by which to measure the stability. Hypothesis 1 proposes two metrics to assess the stability: the number of on-time flights and the delay time.

Table 6-17 finally represents the number of on-time flights because the fewer delayed flights would imply more on-time flight. To compare the delay time of operational strategy, table 6-18 includes the summation of the delay time by operational strategy. Table 6-18 only tracked the positive value of delay time, not consider the negative delay time from the early departure.

Table 6-18 Total Delay Time by Operational Strategy: Nominal Weather

Flight Arrival	Ideal_ FCFS (hour)	Ideal_ SDT (hour)	Largest_ FCFS (hour)	Largest_ SDT (hour)	Resources
Busy-Weekday	3200.52	2990.06	2809.53	2466.25	Worst
Bust-Weekend	4209.46	3790.68	3575.00	3408.72	Worst
Normal-Weekday	2377.00	2216.41	1999.80	1933.59	Worst
Normal-Weekend	2580.81	2427.39	2191.29	2121.14	Worst

The highlighted column implies a smaller delay time. Regardless of the schedule variability buffer, SDT demonstrates a better performance than FCFS in terms of the number of delayed flights.

When SDT is assigned as a higher priority on the decision-making process, it provides a more stable solution for the turnaround time with nominal weather condition. In addition, the busy season’s weekend (Ideal case) shows over 400 hours reduction in SDT total delay time in comparison to that of FCFS. Reducing about 400 hours delay in a day contributes to significant savings from the airline’s perspective, and makes flow for the traffic smooth. Operations in normal season shows a reduction of about 150 hours when following the ideal schedule variability buffer.

Even though a fewer number of hours are reduced when following the largest schedule variability buffer, the table indicates SDT has better performance regardless of the schedule variability buffer or arrival scenarios.

Hypothesis 3-1

If the scheduled departure time is assigned as a higher priority, then it will result in a more stable solution for turnaround time.

In terms of aircraft queuing, hypothesis 3-1 proposes that the scheduled departure time strategy will produce a more stable solution than the FCFS strategy. That hypothesis is proved under the nominal weather condition. After comparing the operational strategy when the weather is off-nominal, the final analysis of the hypothesis will be discussed.

6.4 Experiments Evaluation under Off-Nominal Condition

As mentioned in section 5.4.2, off-nominal weather has 15.52 % delay except the boarding and deboarding execution. To analyze the extreme case, the results assume that the weather has been an off-nominal condition all day.

6.4.1 First-Come-First-Served (FCFS)

Section 6.4.1 consists of the results when the operational strategy takes FCFS under the off-nominal weather condition.

6.4.1.1 Busy (Level of Congestion) – Weekday

This part includes the output of the simulation after running it with the FCFS strategy. It applies the busy season's weekday arrival schedule under the off-nominal weather condition.

Figure 6-26 shows the departure delay time of each arrival from the busy season's weekday schedule. It follows the strategy: First Come First Served. For that case, it relies on their demand time.

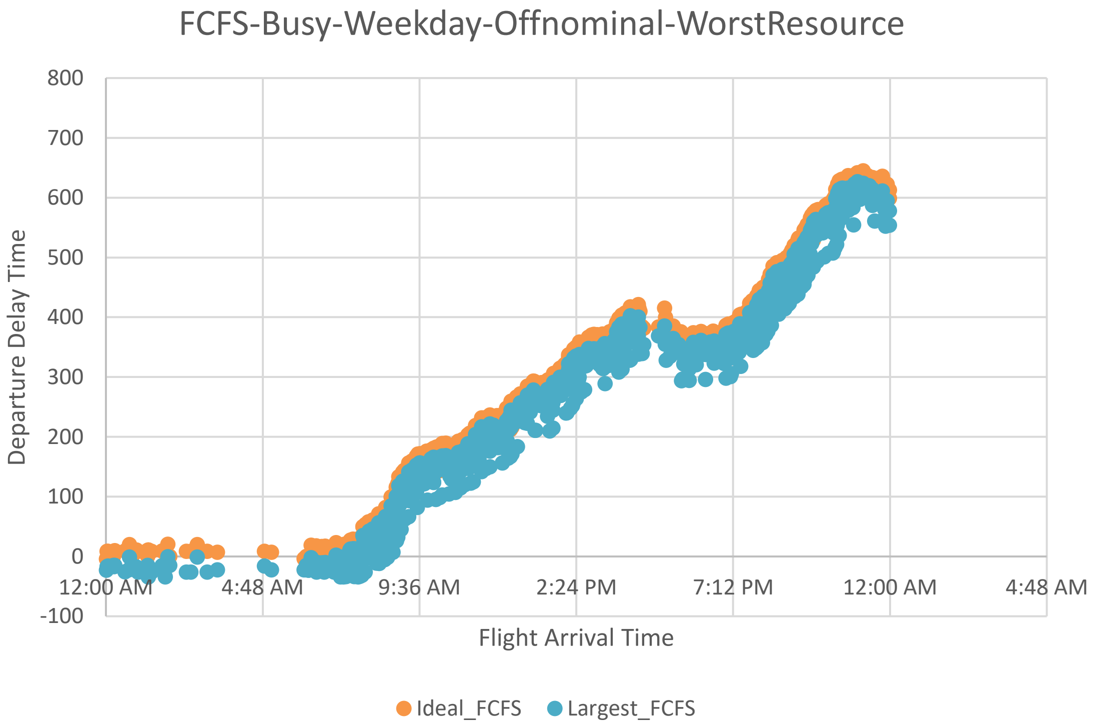


Figure 6-26 Departure Delay Distribution – FCFS, Busy, Weekday, Off-Nominal Weather, and Worst Resources

For the resources, it operates with the worst case scenario. Thus, it has a total of 25 resources for deboarding, boarding, cleaning, loading, unloading, refueling, supplying water, and waste water activity, and a total of 50 resources for catering activity.

In terms of the number of early departures, the ideal case has eight early departure because of the strict schedule due to the zero buffer time. Unlike the ideal, the largest case has 113 early departure. It is distributed only in early morning.

A total of 1024 flights is evaluated as a delayed flight for the ideal case of the schedule variability buffer. For the largest case of the schedule variability buffer, a total of 1020 flights is labeled as a delayed flight.

The longest delay time is around ten and a half hours for the ideal case, and ten hours for the largest case; the largest case has slightly shorter than the ideal case. That flight arrived around 11 pm for both cases. Since the same case under the nominal scenario made the longest delay time about six hours, it is close to twice of that. The insufficient resources and the weather impact would be the reason for the longer delay. It will be discussed again when checking the result of the best case of the resources.

Two peaks are observable around 4 pm and 11 pm. After 4 pm, the departure delay time has a decreasing trend, but the decreasing portion is shorter than the nominal case. It shows the recovery time, but weather impact disturbs the system’s recovery. Due to the night rush hour, the delay time has an increasing trend again.

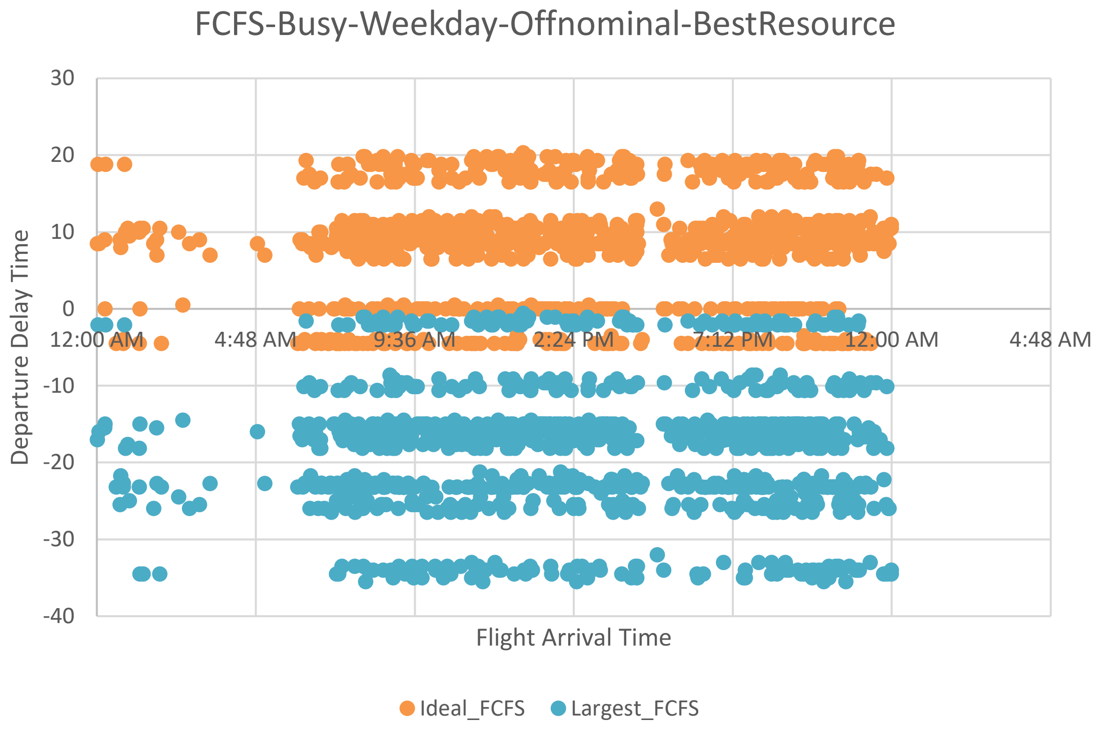


Figure 6-27 Departure Delay Distribution – FCFS, Busy, Weekday, Off-Nominal Weather, and Best Resources

Figure 6-27 shows the departure delay time of each arrival by the FCFS strategy. For the resources, it follows the best case of a number of resources. Thus, it has an unlimited number of resources for every activity: deboarding, boarding, catering, cleaning, loading, unloading, refueling, supplying water, and waste water activity.

For the worst case of the number of resources, it has an increasing trend about the departure delay time. Unlike the worst case, the best case has multiple strip-shaped distributions. Thus, even though under the off-nominal weather condition, the number of resources has a significant contribution to reducing the departure delay time.

When looked at the difference between the ideal case and the largest case of the schedule variability buffer, the number of early flight departure and the number of delayed flights shows the difference. The ideal cases are mainly located in upwards area of the x-axis, and the largest cases are mainly located in the downwards area of the x-axis.

For the ideal case of the schedule variability buffer, there is a total of 214 flights from 1103 arrived flights are evaluated as a delayed flight. When the simulation ran under the nominal condition, there are few delayed flights. Since there is no buffer time, the weather impact cannot be absorbed. The system veils the weather impact, and it is exposed as a delay time. Additionally, the total of 122 flights had early departure than their scheduled departure time.

For the largest case of the schedule variability buffer, there is no flight, which identified as a delayed flight. It means the buffer time absorb the weather impact properly. In that case, a total of 1103 flights had early departure than their scheduled departure time, which means having a negative delay time value.

Table 6-19 Statistics of Busy – Weekday with FCFS Strategy – Off nominal Weather

Schedule Variability Buffer	Resources	Delayed Number of Flights	Early Flight Departure
Ideal	Worst	1024	8
Ideal	Best	214	122
Largest	Worst	972	113
Largest	Best	0	1103

Table 6-19 includes the number of delayed flights and the number of early flight departure by schedule variability buffer and number of resources scenario. Regarding the nominal condition, the schedule variability buffer makes 33 flights differences about the number of delayed flights when following the worst case of resources (See table 6-5). However, under the off-nominal condition, the number of delayed flights dropped 52 flights from the ideal to largest schedule variability buffer. As with the best case of resources, the schedule variability buffer has a significant contribution to reducing the delay in the worst case of resources.

6.4.1.2 Busy (Level of Congestion) – Weekend

This part evaluates the output of the simulation after running it by the FCFS strategy with the busy season's weekend arrival schedule. The simulation runs under the off-nominal condition.

Figure 6-28 shows the departure delay time of each arrival by FCFS strategy from the busy season's weekend schedule. As mentioned, the weather has been severe all day. For the resources, it follows the worst case scenario.

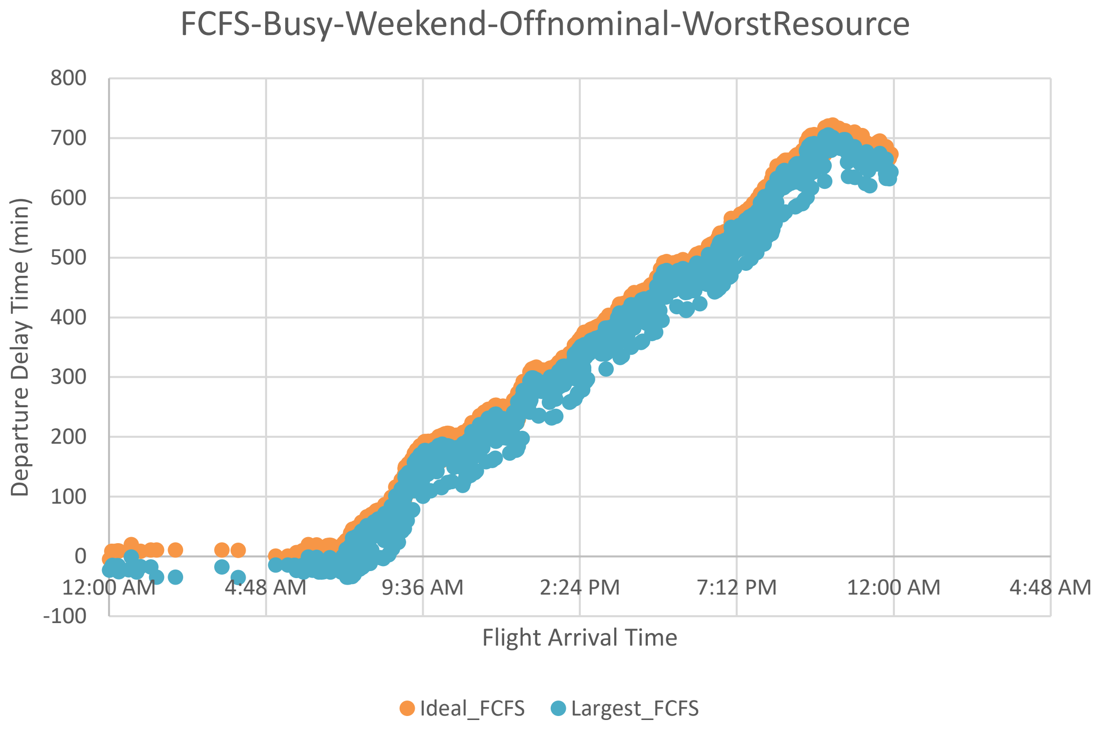


Figure 6-28 Departure Delay Distribution – FCFS, Busy, Weekend, Off-Nominal Weather, and Worst Resources

When it follows the ideal case of the schedule variability buffer, there are a total of 1058 delayed flights. For the largest case of the schedule variability buffer, a total of 975 flights is identified as a delayed flight.

Regarding the early departure, a total of six flights make an early departure than their scheduled departure time when it follows the ideal case. On the other hand, when it follows the largest case, there are a total of 85 early flight departures.

There is an increasing trend from 7 am. It hits a peak around 10 pm and has a decreasing trend after that. Unlike the previous cases, the longest delay time does not show a decided difference. The longest delay time is around 12 hours for both cases. Weather impact makes around five hours differences for the longest delay time.

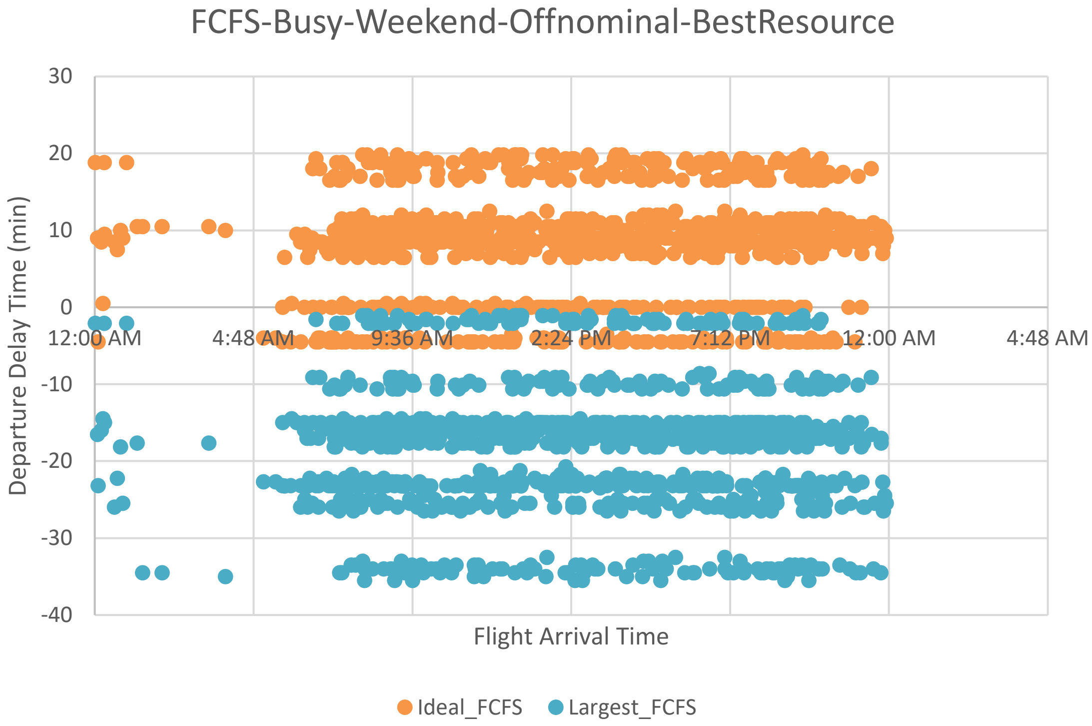


Figure 6-29 Departure Delay Distribution – FCFS, Busy, Weekend, Off-Nominal Weather, and Best Resources

Figure 6-29 shows the departure delay time of each arrival by FCFS strategy when it follows the best case scenario.

When evaluated the ideal case of the schedule variability buffer, there is a total of 215 delayed flights. However, the longest delay time is 19.8 minutes, which means close to on-time flight. It means severe weather has an effect, but not make an extreme situation if there are a numerous number of resources and those are able to work. Total 123 of 1119 flights had early departure than their scheduled departure time, which finished the ground handling activities in advance.

For the largest case of the schedule variability buffer, there is no flight, which labeled as a delayed flight. In other words, the schedule variability buffer works well as a buffer time. All flights were ready to take-off earlier than their scheduled departure time, which means having a negative delay time value.

Table 6-20 Statistics of Busy – Weekend with FCFS Strategy – Off nominal Weather

Schedule variability buffer	Resources	Delayed Number of Flights	Early Flight Departure
Ideal	Worst	1058	6
Ideal	Best	215	123
Largest	Worst	1014	85
Largest	Best	0	1119

Table 6-20 includes the number of delayed flights and the number of early flight departure by schedule variability buffer and number of resources scenario. The ideal case makes around 20 % delayed flights, but the largest case results in 100% on-time performance.

In comparison with the nominal condition, the busy season's weekend case does not show the great impact of the schedule variability buffer. For the worst case of the resources, the case under nominal condition dropped 53 flights from the ideal case to largest case (See table 6-6).

However, table 6-20 shows reducing 44 flights from the ideal case to the largest case. The schedule variability buffer still works suitably and shows its effect, but evaluation between the weather conditions is not available when referring only the number of delayed flights. Thus, in section 6.4.1.5, the more metrics will be tracked and discussed to figure out the impact of the schedule variability buffer.

6.4.1.3 Normal (Level of Congestion) – Weekday

This part illustrates the output of the simulation after running it by the FCFS strategy with the normal season's weekday arrival schedule.

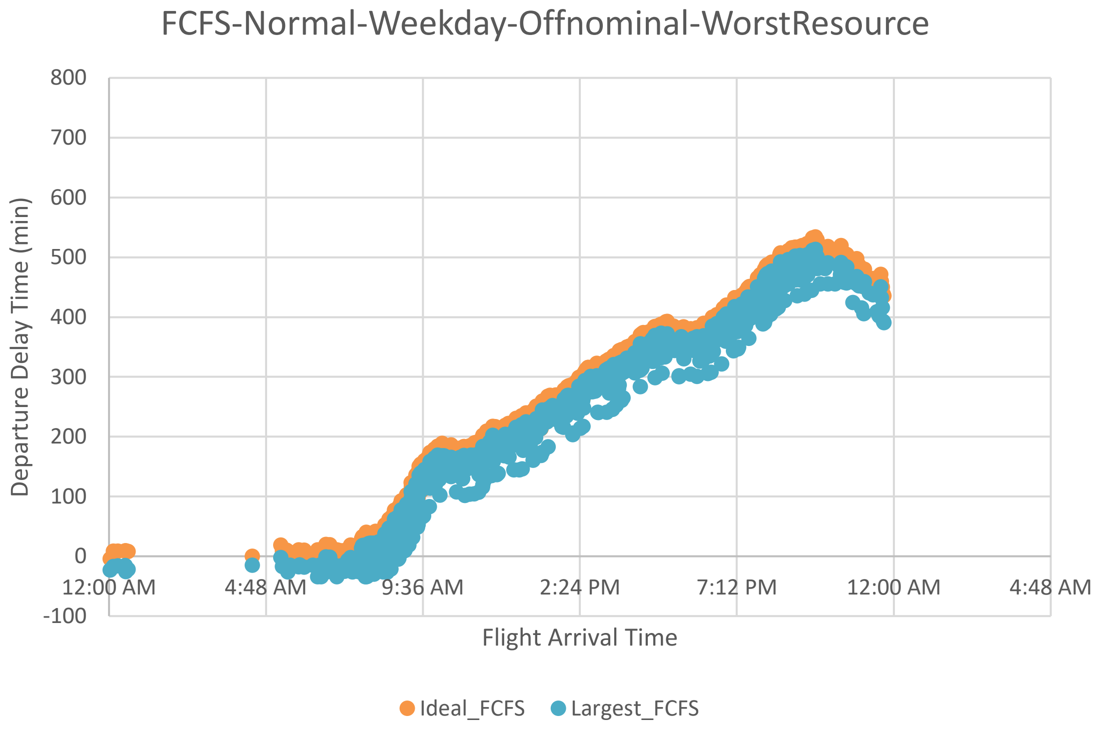


Figure 6-30 Departure Delay Distribution – FCFS, Normal, Weekday, Off-Nominal Weather, and Worst Resources

Figure 6-30 shows the departure delay time of each arrival by FCFS strategy from the normal season's weekday schedule. For the resources, it takes the worst scenario. The whole process takes place under the off-nominal weather condition.

There is a dramatic increase in the morning rush hour. After that period, the distribution still increases until 10 pm and decreases due to the less number of flights. After 5 pm, the nominal case made a decreasing trend clearly, but there is a vague decreasing trend with the naked eye. When tracked the delay time of each flight, the system took a recovery period at that time, but it is pretty shorter than the nominal case.

It has a total of 951 flights in a day. For the ideal case of the schedule variability buffer, there are a total of 893 flights, which are identified as a delayed flight. The longest delay time is around nine hours that indicates almost twice of the nominal condition. Regarding the early departure, five flights are tracked as an early departed flight.

For the largest case of the schedule variability buffer, a total of 839 flights are evaluated as a delayed flight. The longest delay time was slightly more than eight hours. When investigated the number of early departures, 84 flights make an early departure.

Although the normal season’s weekday has the least traffic, the weather impact appears dramatically. However, the schedule variability buffer absorbs that impact and tries to reduce the delay about 40 minutes. It shows that the buffer time responds accurately in off-nominal condition.

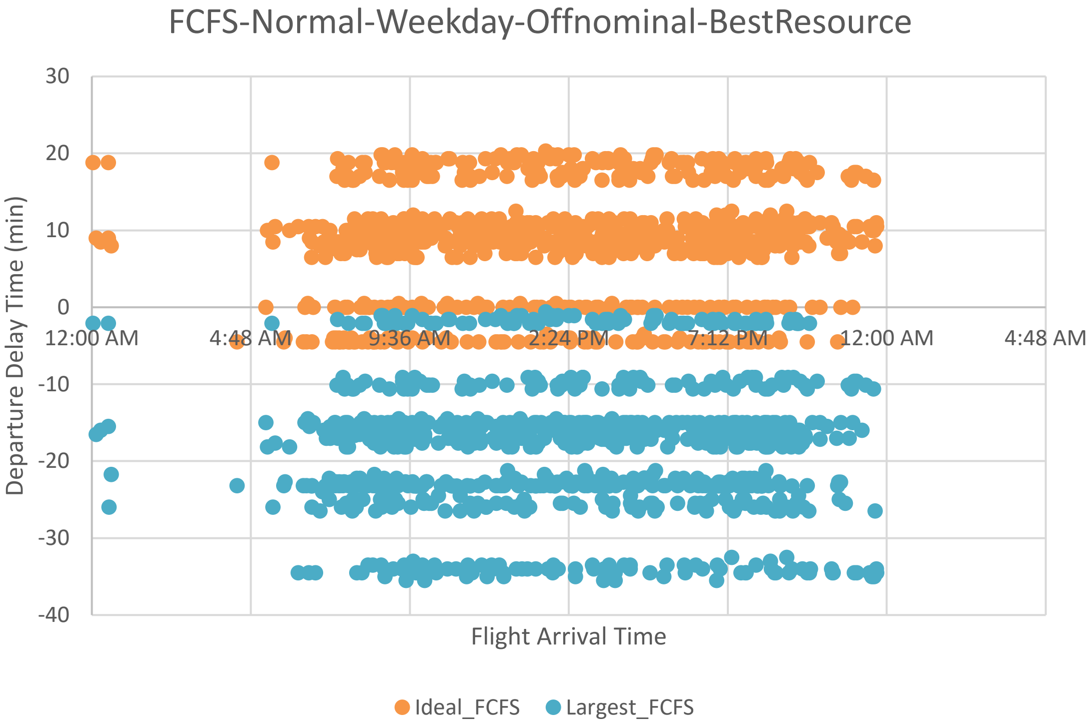


Figure 6-31 Departure Delay Distribution – FCFS, Normal, Weekday, Off-Nominal Weather, and Best Resources

Figure 6-31 shows the departure delay time of each arrival by FCFS strategy with the best case for the resources. Unlike the nominal scenarios, the maximum value of y-axis is 30 minutes.

The best case has multiple strip-shaped distributions whenever applying the ideal case or the largest case for the schedule variability buffer. However, even though there is similar shaped distribution, each case of the schedule variability buffer show the different performances in terms of the number of delayed flights. The ideal cases are positioning on the positive region of the y-axis, but the largest cases are positioning on the negative region of the y-axis.

The arrival scenario has a total of 951 flights when loading the schedule of the normal season's weekday. For the largest case of the schedule variability buffer, no delayed flight is observed like the busy season's cases. It means all flights get on-time performance. Thus, all flights finished all necessary activities before their scheduled departure time, which means having a negative delay time value.

When the ideal case of the schedule variability buffer is applied, there are a total of 187 delayed flights as a result. In terms of the early flight departure, a total of 98 flights had early departure than their scheduled departure time.

Table 6-21 includes the number of delayed flights and the number of early flight departure by schedule variability buffer and number of resources scenario.

Table 6-21 Statistics of Normal – Weekday with FCFS Strategy – Off nominal Weather

Schedule Variability Buffer	Resources	Delayed Number of Flights	Early Flight Departure
Ideal	Worst	893	5
Ideal	Best	187	98
Largest	Worst	839	84
Largest	Best	0	951

The impact of the schedule variability buffer distinct regardless of the resources. The number of delayed flights proved the ability. When the system operates with the worst resources, the nominal case shows 45 flights decrease in the number of delayed flights, but the off-nominal case indicates 54 flights decrease.

6.4.1.4 Normal (Level of Congestion) – Weekend

This part introduces the output of the simulation after running it by the FCFS strategy with the normal season's weekend arrival schedule.

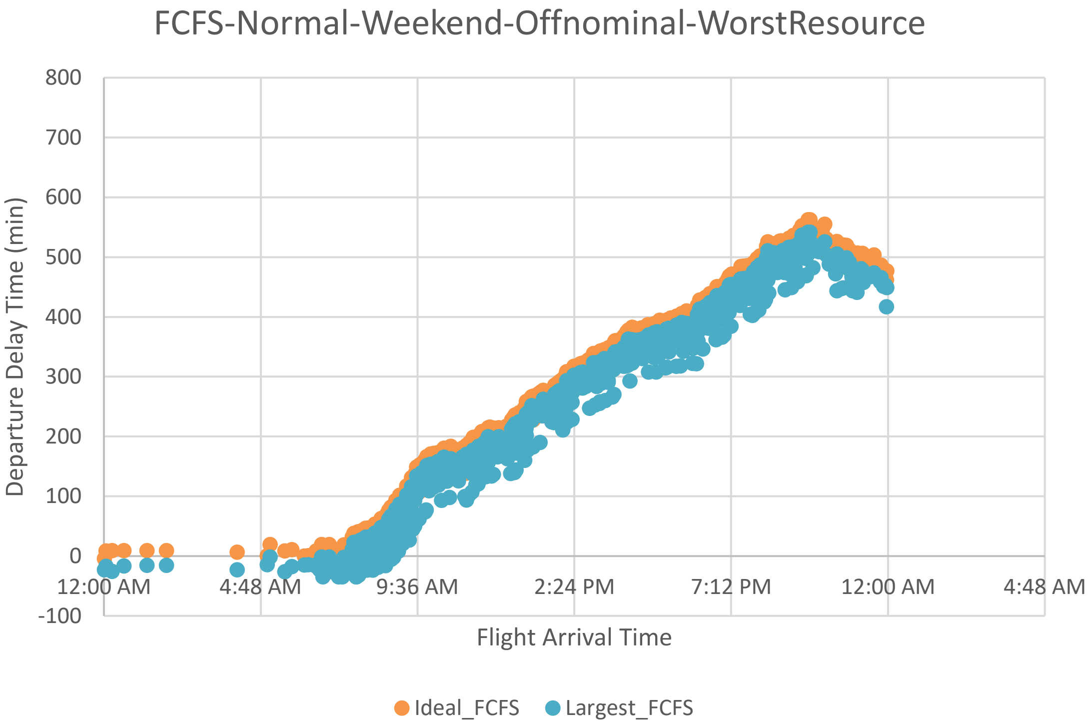


Figure 6-32 Departure Delay Distribution – FCFS, Normal, Weekend, Off-Nominal Weather, and Worst Resources

Figure 6-32 shows the departure delay time of each arrival by FCFS strategy from the normal season's weekend schedule. It operates under the off-nominal weather condition and follows the worst case's scenario for the number of resources.

Normal season's weekend has the traffics under the one thousand. The plot shows a steady increase in the departure delay time until 10 pm. There are no prominent changes in the slope. The decreasing trend appears in the late night due to the reduced traffics.

A total of 913 flights are classified as a delayed flight for the ideal case of the schedule variability buffer. The longest delay time is around nine hours for that case. When the system works with the largest schedule variability buffer, a total of 864 flights are identified as a delayed flight. The longest delay time is around nine hours, but the largest case has slightly shorter than the ideal case. It also occurred at around 10 pm.

In terms of the early departure, the ideal case has five early departure. On the other hand, the largest case has a total of 81 early departure.

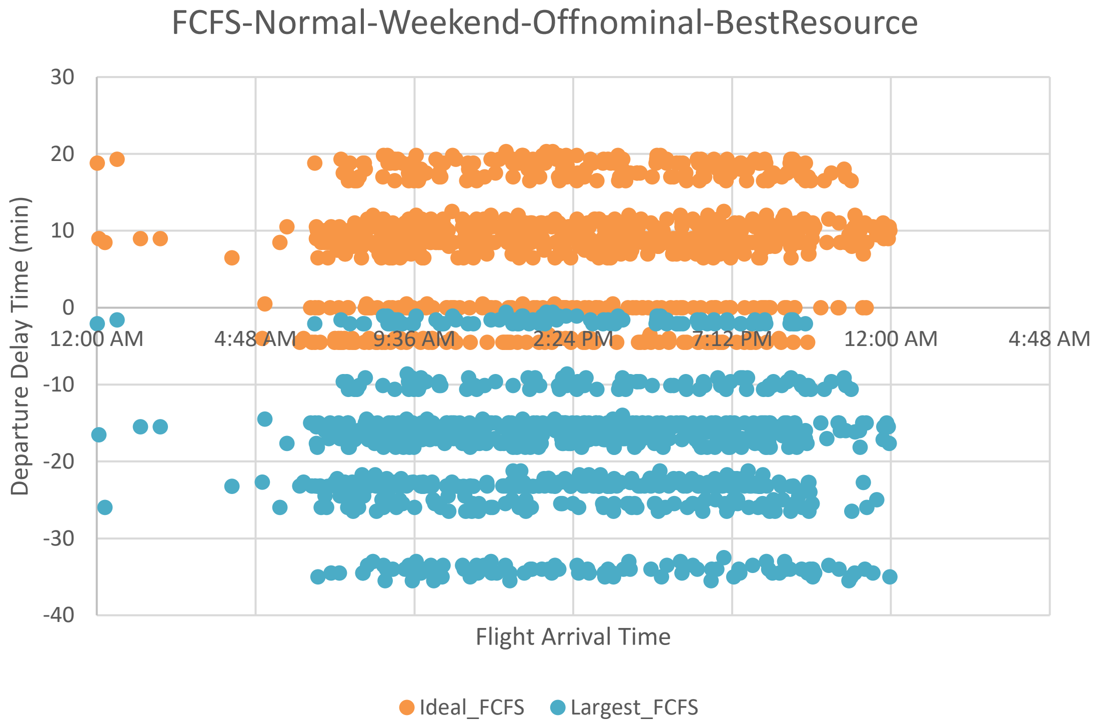


Figure 6-33 Departure Delay Distribution – FCFS, Normal, Weekend, Off-Nominal Weather, and Best Resources

Figure 6-33 shows the departure delay time of each arrival by FCFS strategy with the best resources. It is similar to the previous cases.

For the ideal case of the schedule variability buffer, a total of 187 flight from 967 arrived flights are labeled as a delayed flight. Furthermore, a total of 98 flights had early departure than their scheduled departure time.

For the largest case of the schedule variability buffer, there is no flight, which classified as a delayed flight. Thus, all 967 arrived flights made their departure earlier than their scheduled departure time. Those have finished all the ground handling activities early, so the system assigned their departure.

Table 6-22 represents the number of delayed flights and the number of early flight departure by schedule variability buffer and number of resources scenario.

Table 6-22 Statistics of Normal – Weekend with FCFS Strategy – Off nominal Weather

Schedule Variability Buffer	Resources	Delayed Number of Flights	Early Flight Departure
Ideal	Worst	913	5
Ideal	Best	187	98
Largest	Worst	864	7
Largest	Best	0	967

According to table 6-22, there are 49 flights differences between the ideal case and largest case when the system follows the worst case of resources. For the best case of the resources, the schedule variability buffer produces 187 flight differences. Therefore, the system proves the effect of the schedule variability buffer as a padding as well.

6.4.1.5 Conclusion

Tables 6-23 and 6-24 show the results of the simulator when running it by the operational strategy ‘FCFS (First-Come-First-Served)’ under the off-nominal weather condition. Table 6-23 represents the results of the busy season, and table 6-24 represents the results of the normal season.

When the simulation follows the worst case of a number of resources, the lowest delay ratio is 88.12%, and the highest delay ratio is 94.55%. Due to the weather impact, the overall delay ratio and time are increased over that of the nominal weather’s case.

Regarding the best case number of resources, the FCFS with the largest schedule variability buffer produces no delay even if the off-nominal weather condition. Since the ideal case has about 20% delay, it proves that the schedule variability buffer incorporates the delay due to severe weather. In case of the sufficient number of resources, the schedule variability buffer still plays its role.

Table 6-23 Performance of Simulator: Busy season (FCFS under Off-nominal Weather)

Flight Arrival	**Scenario**		**Delayed flight**	**Early Departure**	**Delay Ratios (%)**	**Longest delay time (min)**
1103 (Weekday)	Resource	Worst	1024	8	92.84	644.8
	Buffer	Ideal				
	Resource	Worst	972	113	88.12	626.5
	Buffer	Largest				
	Resource	Best	214	122	19.4	20.3
	Buffer	Ideal				
	Resource	Best	0	1103	0	No Delay
	Buffer	Largest				
1119 (Weekend)	Resource	Worst	1058	6	94.55	721.8
	Buffer	Ideal				
	Resource	Worst	1014	85	90.61	705.5
	Buffer	Largest				
	Resource	Best	215	123	19.21	19.8
	Buffer	Ideal				
	Resource	Best	0	1119	0	No Delay
	Buffer	Largest				

Table 6-24 Performance of Simulator: Normal season (FCFS under Off-nominal Weather)

Flight Arrival	Scenario		Delayed flight	Early Departure	Delay Ratios (%)	Longest delay time (min)
951 (Weekday)	Resource	Worst	893	5	93.90	534.3
	Buffer	Ideal				
	Resource	Worst	839	84	88.22	513.4
	Buffer	Largest				
	Resource	Best	187	98	19.66	20.3
	Buffer	Ideal				
	Resource	Best	0	951	0	No Delay
	Buffer	Largest				
967 (Weekend)	Resource	Worst	913	5	94.41	562.3
	Buffer	Ideal				
	Resource	Worst	864	81	89.34	541.4
	Buffer	Largest				
	Resource	Best	187	98	19.33	20.3
	Buffer	Ideal				
	Resource	Best	0	967	0	No Delay
	Buffer	Largest				

To compare both scenarios, Table 6-25 specifies the number of delayed flights when the system takes the off-nominal and nominal scenarios.

Table 6-25 Comparison of the Off-nominal and Nominal Scenarios' Performance: FCFS Strategy

Level of Congestion	Schedule Variability Buffer	Resources	Delayed Flights (Off-nominal)	Delayed Flights (Nominal)
Busy- Weekday	Ideal	Worst	1024	983
Busy- Weekday	Largest	Worst	972	950
Busy- Weekday	Ideal	Best	214	3
Busy- Weekday	Largest	Best	0	0
Busy- Weekend	Ideal	Worst	1058	1028
Busy- Weekend	Largest	Worst	1014	975
Busy- Weekend	Ideal	Best	215	1
Busy- Weekend	Largest	Best	0	0
Normal-Weekday	Ideal	Worst	893	846
Normal-Weekday	Largest	Worst	839	801
Normal-Weekday	Ideal	Best	187	1
Normal-Weekday	Largest	Best	0	0
Normal-Weekend	Ideal	Worst	913	880
Normal-Weekend	Largest	Worst	864	820
Normal-Weekend	Ideal	Best	187	1
Normal-Weekend	Largest	Best	0	0

Except for the combination of the largest schedule variability buffer and the best resources, all cases show the off-nominal cases have more number of delayed flights. In particular, there are considerable gaps for the combination of the ideal schedule variability buffer and the best resources.

Table 6-26 indicates the change in the number of delayed flights from the ideal to the largest schedule variability buffer:

$$\Delta = \text{Number of delayed flights(ideal case)} - \text{Number of delayed flights(largest case)}$$

Table 6-26 Comparison of the Off-nominal and Nominal Scenarios' Performance: FCFS Strategy

Level of Congestion	Resources	Δ: Off-nominal	Δ: Nominal
Busy- Weekday	Worst	52	33
Busy- Weekday	Best	214	3
Busy- Weekend	Worst	44	53
Busy- Weekend	Best	215	1
Normal- Weekday	Worst	54	45
Normal- Weekday	Best	187	1
Normal- Weekend	Worst	49	60
Normal- Weekend	Best	187	1

The highlighted cells represent the larger of the off-nominal and nominal scenarios. Except for the busy and normal season's weekend with the worst resources, all other cases show that the off-nominal scenario is better. That is because the system is long clogged with delayed flights regardless of the schedule variability buffer.

As the number of delayed flights is not the only metric to measure delay, the following table shows the other metric: the total delay time. Table 6-27 indicates the change in the total delay time from the ideal to the largest schedule variability buffer:

$$\delta = \text{Total Delay Time (ideal case)} - \text{Total Delay Time (largest case)}$$

Table 6-27 Comparison of the Off-nominal and Nominal Scenarios' Performance: FCFS Strategy

Level of Congestion	Resources	δ: Off-nominal	δ: Nominal
Busy- Weekday	Worst	460.33	390.99
Busy- Weekday	Best	164.58	62.71
Busy- Weekend	Worst	474.76	454.45
Busy- Weekend	Best	166.62	63.38
Normal- Weekday	Worst	401.13	377.20
Normal- Weekday	Best	142.74	54.55
Normal- Weekend	Worst	410.93	389.52
Normal- Weekend	Best	144.80	55.78

The highlighted cells indicate the larger of the off-nominal and nominal scenarios. All cases show that the change in the total delay time from the ideal to the largest schedule variability buffer is greater in the off-nominal scenarios. It indicates that the schedule variability buffer is more effective in the unexpected situation that includes the potential delay factor.

6.4.2 Schedule Departure Time (SDT)

Section 6.4.2 consists of the results when the operational strategy takes schedule departure time under off-nominal weather condition.

6.4.2.1 Busy (Level of Congestion) – Weekday

This part includes the output of the simulation after running it with busy season's weekday arrival schedule under the off-nominal weather condition.

Figure 6-34 shows the departure delay time of each arrival by SDT strategy under the off-nominal weather condition. The flight arrival scenario is from the busy season's weekday. For the resources, it follows the worst case. Thus, it has a total of 25 resources for deboarding, boarding, cleaning, loading, unloading, refueling, supplying water, and waste water activity, and a total of 50 resources for catering activity.

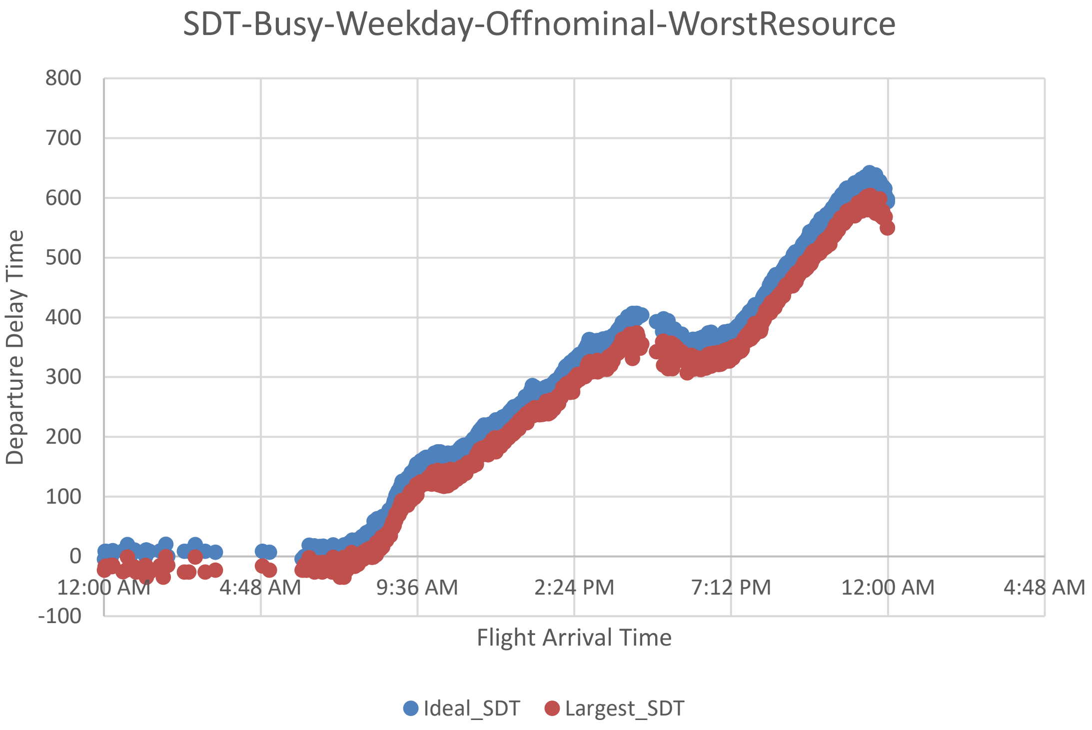


Figure 6-34 Departure Delay Distribution – SDT, Busy, Weekday, Off-Nominal Weather, and Worst Resources

Around 9 am, the distribution shows the heavy traffic with the steep curve. From the end of the morning rush hour, the delay still makes an increasing trend. After 4 pm, there is a decreasing trend of departure delay time until 6 pm. The reason for recovery is the reduced number of flight arrivals. However, due to the night rush hour, the delay time has an increasing trend again until 11 pm. Since the environment has a limited quantity for the resources, the departure delay time is sensitive to the number of handling flight. The longest delay time is around ten and a half hours for the ideal case and ten hours for the largest case.

Table 6-28 includes the number of delayed flights and the number of early flight departures by schedule variability buffer and number of resources scenario. The best case of the resources shows identical results with the result of the FCFS strategy. The full departure delay distribution of best case is illustrated in Appendix G.

Table 6-28 Statistics of Busy – Weekday with SDT Strategy – Off nominal Weather

Schedule Variability Buffer	Resources	Delayed Number of Flights	Early Flight Departure
Ideal	Worst	1020	11
Ideal	Best	214	122
Largest	Worst	951	122
Largest	Best	0	1103

A total of 1020 flights is evaluated as a delayed flight for the ideal case of the schedule variability buffer when the worst resources are applied. Unlike the nominal scenario, there are more than 200 flights delayed when the best resources are applied. For the largest case of the schedule variability buffer, a total of 951 flights are identified as a delayed flight.

A total of 214 flights from 1103 arrived flights are evaluated as a delayed flight for the ideal case of the schedule variability buffer. However, when tracking all the delayed time, all have less than 30 minutes (See Appendix G). Therefore, it is not a severe delay such as the worst case of the resources.

The worst case of the resources has a growing trend of the departure delay time, and the longest delay time is recorded around ten hours. However, the best case of the resources represents the reduced number of delayed flights and the shorter delay time. Thus, it is evident that the number of resources has an excellent contribution to reducing the departure delay time.

6.4.2.2 Busy (Level of Congestion) – Weekend

This part consists of the output of the simulation after running it with the busy season's weekend arrival schedule. It assumes the weather has been sick all day.

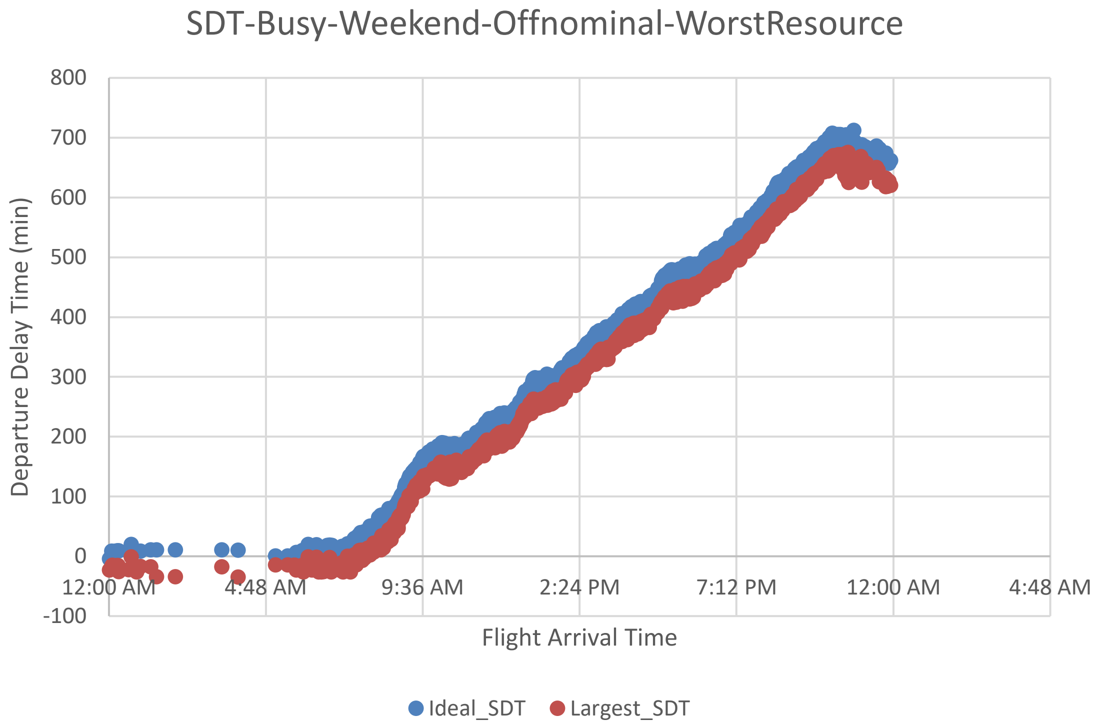


Figure 6-35 Departure Delay Distribution – SDT, Busy, Weekend, Off-Nominal Weather, and Worst Resources

Figure 6-35 shows the departure delay time of each arrival by SDT strategy with the busy season's weekend schedule. It illustrates a peak around 11 pm for both schedule variability buffer. The longest delay time is around twelve hours for the ideal case and around eleven hours for the largest case. Since the busy season with weekend schedule handles the most massive traffic under the off-nominal weather condition, it has a longer delay time. In that case, the departure delay distribution exposes the morning rush hour as well.

Table 6-29 includes the number of delayed flights and the number of early flight departures by schedule variability buffer and number of resources scenario. The best case of the resources shows identical results with the result of the FCFS strategy. The full departure delay distribution of best case is illustrated in Appendix G

Table 6-29 Statistics of Busy – Weekend with SDT Strategy – Off nominal Weather

Schedule Variability Buffer	Resources	Delayed Number of Flights	Early Flight Departure
Ideal	Worst	1049	9
Ideal	Best	215	123
Largest	Worst	984	101
Largest	Best	0	1119

A total of 1049 flights are identified as a delayed flight for the ideal case of the schedule variability buffer. For the largest case of the schedule variability buffer, a total of 984 flights are labeled as a delayed flight. A total of 215 from the arrival flight are labeled as a delayed flight for the ideal case of the schedule variability buffer. The longest delay time is 19.8 minutes. It means all the delayed time is less than 20 minutes.

For the largest case of the schedule variability buffer, no flight is delayed. In that case, a total of 1119 flights had early departure than their scheduled departure time, which means having a negative delay time value.

6.4.2.3 Normal (Level of Congestion) – Weekday

This part shows the output of the simulation after running it with normal season's weekday arrival schedule under the off-nominal weather condition.

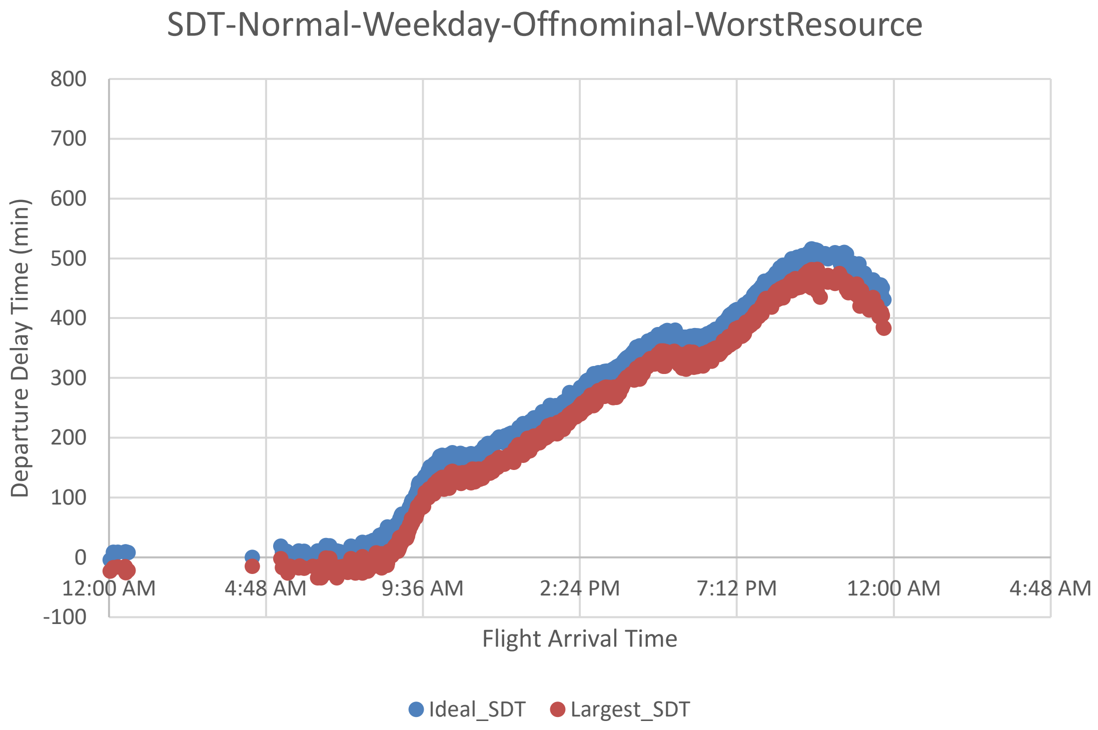


Figure 6-36 Departure Delay Distribution – SDT, Normal, Weekday, Off-Nominal Weather, and Worst Resources

Figure 6-36 shows the departure delay time of each arrival by SDT strategy with the normal season's weekday schedule. For the resources, it sticks the worst scenario.

On the figure, two recovery times are observable around 5 pm and 10 pm. It is shorter than the result of the nominal scenario. It results from the cumulative traffic due to the weather effects. After 5 pm, the distribution made a slightly decreasing trend until 6 pm because the number of flight arrivals slightly declined. Thus, the system can recover in that period. However, due to the night rush hour, the delay time has an increasing trend until 10 pm.

As expected, the longest delay time is longer than the nominal scenario. The detailed comparison will be discussed in conclusion section.

Table 6-30 includes the number of delayed flights and the number of early flight departures by schedule variability buffer and number of resources scenario. The best case of the resources shows identical results with the result of the FCFS strategy. The full departure delay distribution of best case can be seen in Appendix G.

Table 6-30 Statistics of Normal – Weekday with SDT Strategy – Off nominal Weather

Schedule Variability Buffer	Resources	Delayed Number of Flights	Early Flight Departure
Ideal	Worst	879	8
Ideal	Best	187	98
Largest	Worst	814	104
Largest	Best	0	967

There are a total of 951 flights in a day for the normal season's weekday schedule. In terms of the worst case of the resources, a total of 879 flights are classified as a delayed flight for the ideal case of the schedule variability buffer.

On the other hand, the largest case of the schedule variability buffer produces a total of 814 delayed flights. When the system operates with the SDT strategy, the schedule variability buffer does work correctly.

6.4.2.4 Normal (Level of Congestion) – Weekend

This part represents the output of the simulation after running it with normal season's weekend arrival schedule.

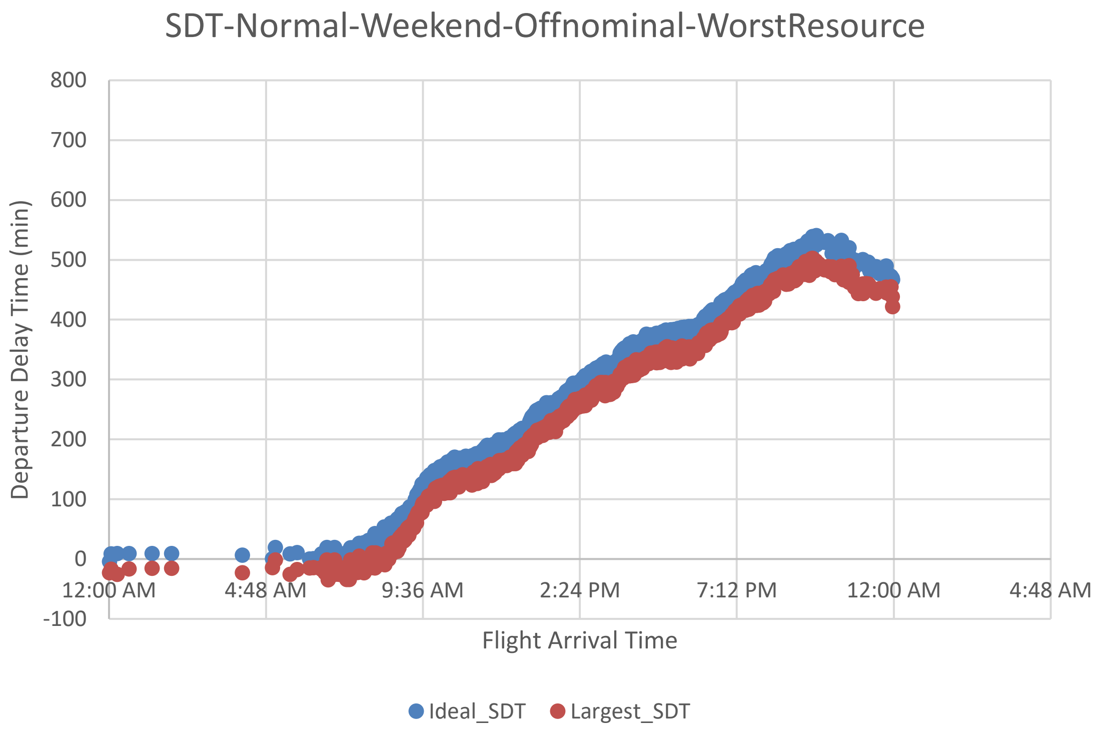


Figure 6-37 Departure Delay Distribution – SDT, Normal, Weekend, Off-Nominal Weather, and Worst Resources

Figure 6-37 shows the departure delay time of each arrival from the normal season's weekend schedule. It operates by SDT strategy and the working day has terrible weather. It has an increasing trend until 10 pm and hits the peak. Due to the reduced number of flights in the night time, it makes reverse trend at that time.

For the ideal case of the schedule variability buffer, a total of 905 flights are evaluated as a delayed flight. The longest delay time is around nine hours, and that flight arrived between 9 pm and 10 pm.

For the largest case of the schedule variability buffer, a total of 837 flights are identified as a delayed flight. The longest delay time is around eight hours. It also occurred between 9 pm and 10 pm.

Table 6-31 includes the number of delayed flights and the number of early flight departures by schedule variability buffer and number of resources scenario. The best case of the resources shows identical results with the result of the FCFS strategy. The full departure delay distribution of best case can be seen in Appendix G

Table 6-31 Statistics of Normal – Weekend with SDT Strategy – Off nominal Weather

Schedule Variability Buffer	Resources	Delayed Number of Flights	Early Flight Departure
Ideal	Worst	905	7
Ideal	Best	187	98
Largest	Worst	837	101
Largest	Best	0	967

6.4.2.5 Conclusion

Table 6-32 and 6-33 show the results of the simulator under the operational strategy 'SDT (Scheduled Departure Time)' under the off-nominal weather condition. Table 6-32 shows the busy season, and table 6-33 shows the normal season.

When the simulation follows the worst case for the number of resources, the lowest delay ratio is 85.59%, and the highest delay ratio is 93.74%. Due to the weather impact, the overall delay ratio and time are more than that of the nominal weather's case.

Regarding the best case of the number of resources, the schedule variability buffer has a critical role to prevent delay. When it follows the ideal schedule variability buffer, there are almost 20% delayed flights.

However, for the largest schedule variability buffer there is no delayed flight. When the system follows the nominal scenario, there were under 1% delayed flight or no delayed flight regardless of the schedule variability buffer if the best case of resources is applied. It implies that if there are influential delay factors such as weather, then the schedule variability buffer has great contribution to reducing delay. It sounds reasonable in the real world, but it results from the simulator's performance. The simulator shows the role of schedule variability buffer correctly, and it can be proof of the reliability.

Table 6-32 Performance of Simulator: Busy season (SDT under Nominal Weather)

Flight Arrival	Scenario		Delayed flight	Early Departure	Delay Ratios (%)	Longest delay time (min)
1103 (Weekday)	Resource	Worst	1020	11	92.47	642
	Buffer	Ideal				
	Resource	Worst	951	122	86.21	604
	Buffer	Largest				
	Resource	Best	214	122	19.4	20.3
	Buffer	Ideal				
	Resource	Best	0	1103	0	No Delay
	Buffer	Largest				
1119 (Weekend)	Resource	Worst	1049	9	93.74	712
	Buffer	Ideal				
	Resource	Worst	984	101	87.93	675.3
	Buffer	Largest				
	Resource	Best	215	123	19.21	19.8
	Buffer	Ideal				
	Resource	Best	0	1119	0	No Delay
	Buffer	Largest				

Table 6-33 Performance of Simulator: Normal season (SDT under Nominal Weather)

Flight Arrival	Scenario		Delayed flight	Early Departure	Delay Ratios (%)	Longest delay time (min)
951 (Weekday)	Resource	Worst	879	8	92.42	516
	Buffer	Ideal				
	Resource	Worst	814	104	85.59	481.5
	Buffer	Largest				
	Resource	Best	187	98	19.66	20.3
	Buffer	Ideal				
	Resource	Best	0	951	0	No Delay
	Buffer	Largest				
967 (Weekend)	Resource	Worst	905	7	93.58	540.5
	Buffer	Ideal				
	Resource	Worst	837	101	86.55	502.5
	Buffer	Largest				
	Resource	Best	187	98	19.33	20.3
	Buffer	Ideal				
	Resource	Best	0	967	0	No Delay
	Buffer	Largest				

To compare the nominal and off-nominal scenarios, table 6-34 illustrates the number of delayed flights by the scenario. Since the largest schedule variability buffer and the best resources cause no delay, those cases are excluded from the table. All cases show that the off-nominal cases have more delayed flights. In particular, there are considerable gaps for the combination of the ideal schedule variability buffer and the best resources.

Table 6-34 Comparison of the Off-nominal and Nominal Scenarios' Performance: SDT Strategy

Level of Congestion	Schedule Variability Buffer	Resources	Delayed Flights (Off-nominal)	Delayed Flights (Nominal)
Busy- Weekday	Ideal	Worst	1020	968
Busy- Weekday	Largest	Worst	951	913
Busy- Weekday	Ideal	Best	214	3
Busy- Weekend	Ideal	Worst	1049	1014
Busy- Weekend	Largest	Worst	984	958
Busy- Weekend	Ideal	Best	215	1
Normal-Weekday	Ideal	Worst	879	829
Normal-Weekday	Largest	Worst	814	796
Normal-Weekday	Ideal	Best	187	1
Normal-Weekend	Ideal	Worst	905	859
Normal-Weekend	Largest	Worst	837	816
Normal-Weekend	Ideal	Best	187	1

Table 6-35 indicates the change in the number of delayed flights from the ideal to the largest schedule variability buffer:

$$\Delta = \text{Number of delayed flights(ideal case)} - \text{Number of delayed flights(largest case)}$$

Table 6-35 Comparison of the Off-nominal and Nominal Scenarios' Performance: SDT Strategy

Level of Congestion	Resources	Δ: Off-nominal	Δ: Nominal
Busy- Weekday	Worst	69	55
Busy- Weekday	Best	214	3
Busy- Weekend	Worst	65	56
Busy- Weekend	Best	215	1
Normal- Weekday	Worst	65	33
Normal- Weekday	Best	187	1
Normal- Weekend	Worst	68	43
Normal- Weekend	Best	187	1

The highlighted cells indicate the large of the off-nominal and nominal scenarios. All cases specify that the off-nominal scenario result in better performances. It represents that the schedule variability buffer is more effective when working with the SDT strategy under the off-nominal weather.

However, the number of delayed flights cannot be the only way to evaluate the delay and schedule variability buffer. Thus, the total delay time is tracked, and the following table shows the results. Table 6-36 indicates the change in the total delay time from the ideal to the largest schedule variability buffer:

$$\delta = \text{Total Delay Time (ideal case)} - \text{Total Delay Time (largest case)}$$

Table 6-36 Comparison of the Off-nominal and Nominal Scenarios' Performance: SDT Strategy

Level of Congestion	Resources	δ: Off-nominal	δ: Nominal
Busy- Weekday	Worst	565.79	523.82
Busy- Weekday	Best	164.58	62.71
Busy- Weekend	Worst	584.96	381.96
Busy- Weekend	Best	166.62	63.38
Normal- Weekday	Worst	470.29	282.82
Normal- Weekday	Best	142.74	54.55
Normal- Weekend	Worst	491.59	306.24
Normal- Weekend	Best	144.80	55.78

The highlighted cells represent the large of the off-nominal and nominal scenarios as well. All cases show that the change in the total delay time from the ideal to the largest schedule variability buffer is greater in the off-nominal scenarios.

In particular, the extreme case 'busy-weekend' proves the positive effect of the schedule variability buffer. It implies that the schedule variability buffer works efficiently with the SDT strategy under the unexpected situation that including the potential delay factor.

6.4.3 Comparison of Operational Strategy under the Off-nominal Scenarios

As mentioned in Section 6.3.3, hypothesis 3-1 proposes that the scheduled departure time strategy will produce a more stable solution than the first-come-first-served strategy. It is proved under the nominal weather condition (See section 6.3.3). Here, it will be discussed that the SDT strategy will produce a more stable solution under the off-nominal scenario or not. Then, the final evaluation of the hypothesis will be stated.

Figures 6-38, 6-39, 6-40, and 6-41 show the departure delay distribution with the SDT strategy and FCFS strategy under the off-nominal weather condition. If the SDT strategy makes a better performance than the FCFS under the off-nominal weather condition, then SDT can be assessed as a more stable solution.

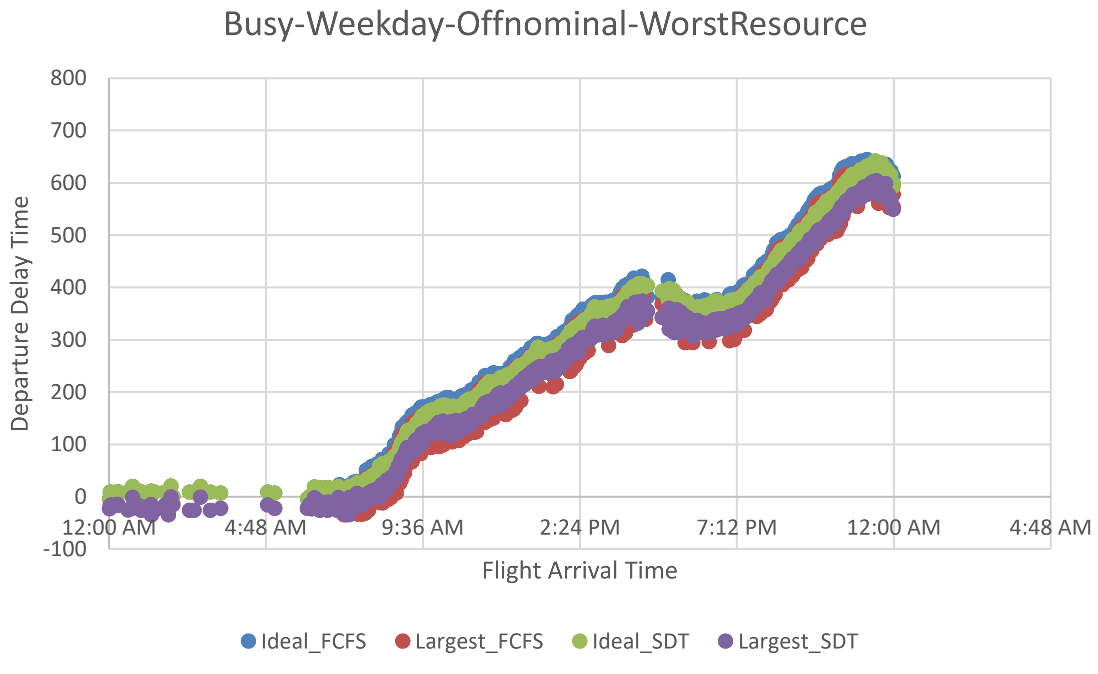


Figure 6-38 Departure Delay Distribution – Busy, Weekday, and Off-nominal Weather

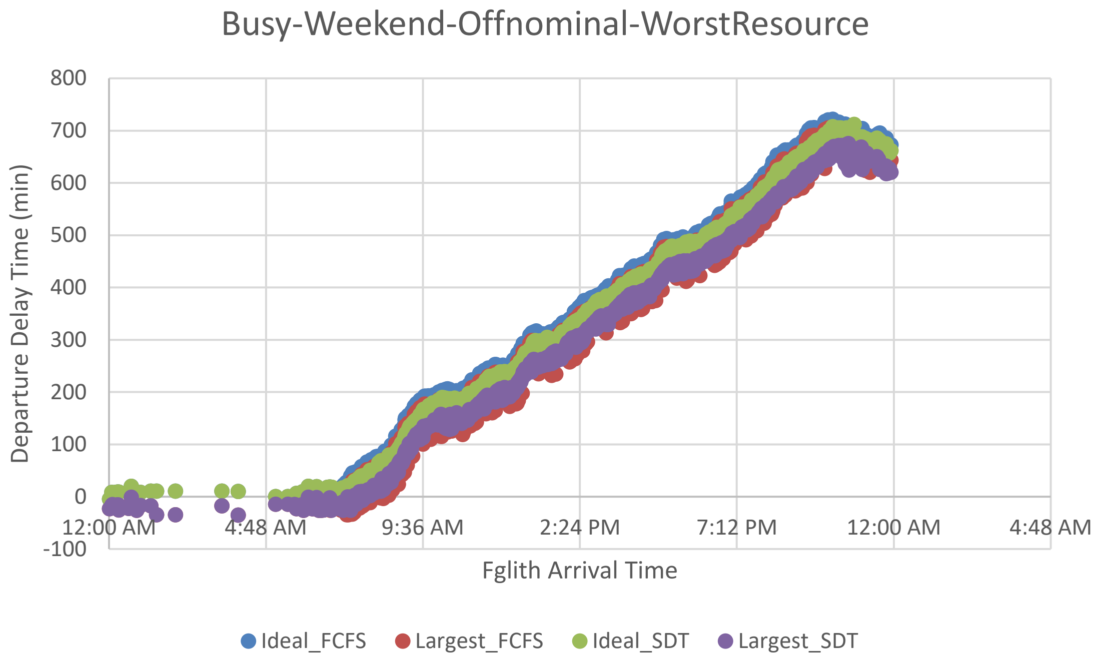


Figure 6-39 Departure Delay Distribution – Busy, Weekend, and Off-nominal Weather

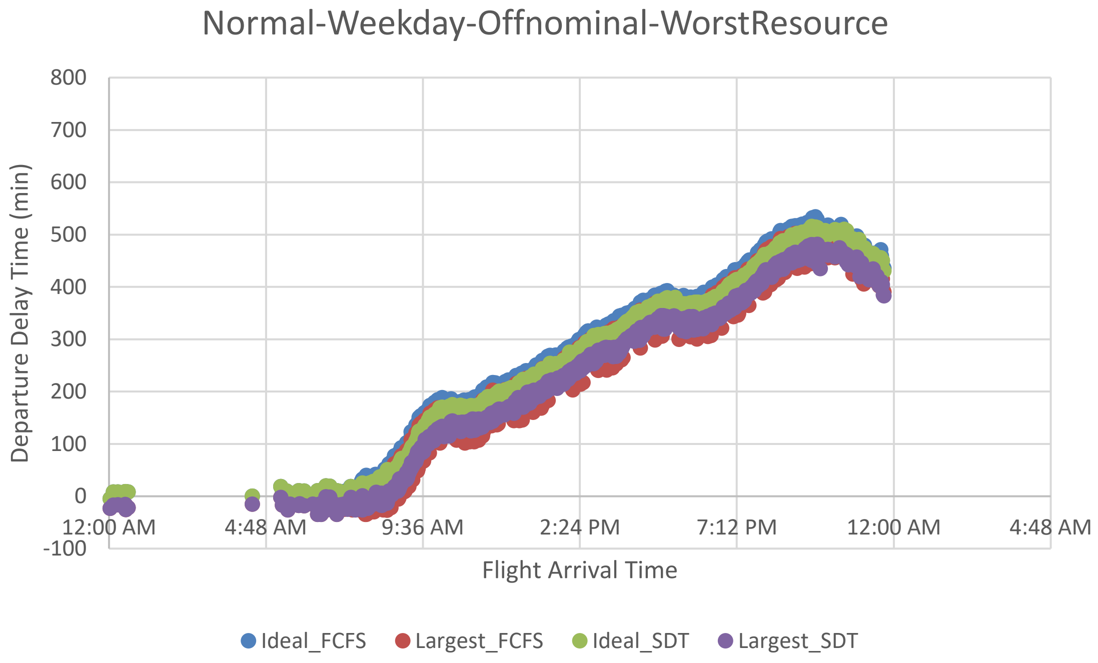


Figure 6-40 Departure Delay Distribution – Normal, Weekday, and Off-nominal Weather

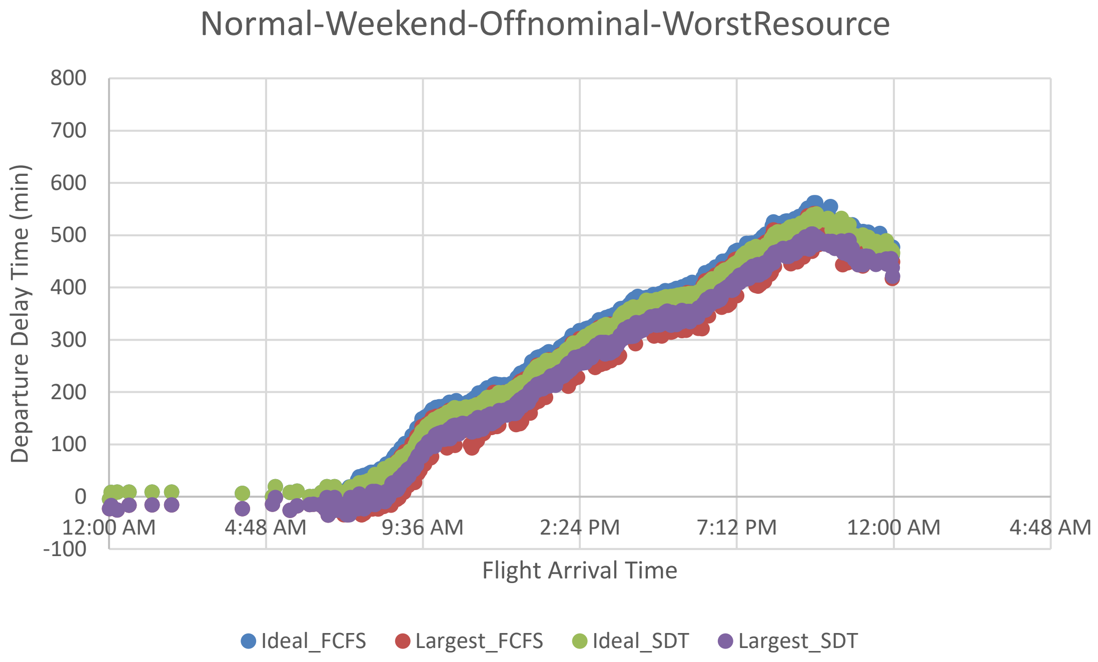


Figure 6-41 Departure Delay Distribution – Normal, Weekend, and Off-nominal Weather

As shown in the results of the nominal weather, FCFS tend to vary wider than SDT under the off-nominal weather. Figures illustrate that the results of SDT are located inside the region of the results of FCFS. In general, the SDT distribution matches with the FCFS distribution when applying the same schedule.

Due to the significant overlaps in the plots, it is hard to draw meaningful conclusions from the plots. Thus, the comparison would be continued with the numerical results.

Table 6-37 shows the number of delayed flights by operational strategy. The highlighted column represents getting less number of delayed flights. Regarding the number of delayed flights, SDT produces a better performance than FCFS regardless of the schedule variability buffer.

Table 6-37 Number of Delayed Flights by Operational Strategy: Off-nominal Weather

Flight Arrival	Ideal_ FCFS	Ideal_ SDT	Largest_ FCFS	Largest_ SDT	Resources
Busy-Weekday	1024	1020	972	951	Worst
Bust-Weekend	1058	1049	1014	984	Worst
Normal-Weekday	893	879	839	814	Worst
Normal-Weekend	913	905	864	837	Worst

Table 6-38 Total Delay Time by Operational Strategy: Off-nominal Weather

Flight Arrival	Ideal_ FCFS (hour)	Ideal_ SDT (hour)	Largest_ FCFS (hour)	Largest_ SDT (hour)	Resources
Busy-Weekday	5657.74	5487.19	5197.41	4921.40	Worst
Bust-Weekend	6645.16	6402.84	6170.39	5817.88	Worst
Normal-Weekday	4284.08	4102.31	3882.94	3632.02	Worst
Normal-Weekend	4536.51	4369.61	4125.57	3878.02	Worst

Table 6-38 represents the summation of the delay time by operational strategy. It only tracked the positive value of delay time, not consider the negative delay time that means the early departure.

The highlighted column implies a smaller delay time. SDT demonstrates a better performance than FCFS in terms of the number of delayed flights with any schedule variability buffer. Table 6-39 indicates the change in the total delay time from the SDT to the FCFS strategy:

$$\Delta = \text{Total Delay Time (SDT strategy)} - \text{Total Delay Time (FCFS strategy)}$$

Table 6-39 Comparison of the Operational Strategy's Performance: Off-nominal Scenario

Flight Arrival	Δ: Ideal (hour)	Δ: Largest (hour)	Resources
Busy-Weekday	-170.55	-276.01	Worst
Bust-Weekend	-242.32	-352.51	Worst
Normal-Weekday	-181.77	-250.92	Worst
Normal-Weekend	-166.9	-242.55	Worst

According to table 6-39, SDT reduces the delay time. The busy season's weekend (Ideal case) shows over 200 hours reduction in SDT total delay time in comparison to that of FCFS. Reducing about 200 hours delay, under severe weather conditions in a day, contributes to significant savings from the airline's perspective, and makes flow for the traffic smooth. Operations in normal season shows a reduction of about 150 hours when following the ideal schedule variability buffer.

Besides table 6-39, table 6-37 demonstrates that SDT reduced the number of delayed flights. Therefore, when SDT is assigned as a higher priority on the decision-making process, it makes a more stable solution for the turnaround time with any weather condition.

Hypothesis 3-1

If the scheduled departure time is assigned as a higher priority, then it will result in a more stable solution for turnaround time.

As a result, it made a success to obtain a more stable solution for the turnaround time with the Scheduled Departure Time: Hypothesis 3-1 has been substantiated.

6.5 Validation of Performance

Section 6.3 and 6.4 introduced the performance of the simulator and evaluated it through the experiments. They illustrate the delay time of departure for each arrival, the number of delayed flights, and the number of early flight departures. The extracted output shows the pattern of delay and the point of the longest delay time. Based on the extracted output and the behavior of the simulation, hypothesis 3 and 3-1 have been substantiated.

To evaluate that the simulation model is valid, the comparison the model to the actual process is required. Thus, the main task of this section compares the experimental results to the real data. The heaviest traffic scenario (Busy season-weekend) has been used for comparison.

6.5.1 Departure Delay Time

Figure 6-42, 6-43, 6-44, and 6-45 illustrate the distribution of delay time for flight departure. In general, flight delay gather around the x-axis, but a few outliers are observed. Furthermore, it is explicit that there is less traffic early in the morning or late in the evening. However, all figures show a long delay time around midnight. Thus, capturing the delay reason will be discussed in section 6.5.2.

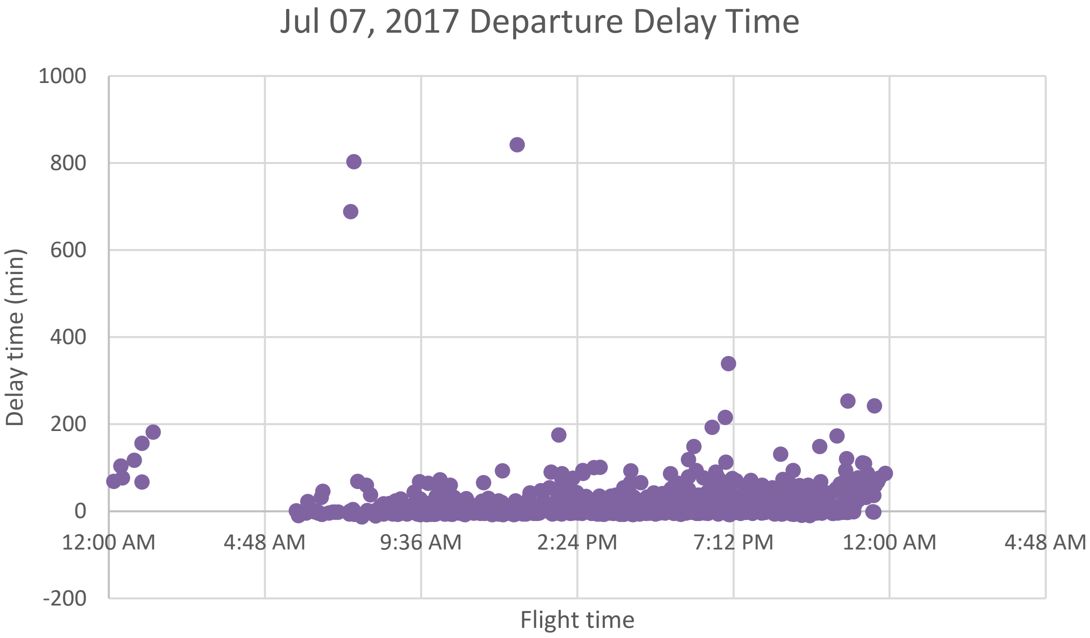


Figure 6-42 Departure Delay Time on Friday, July 07, 2017

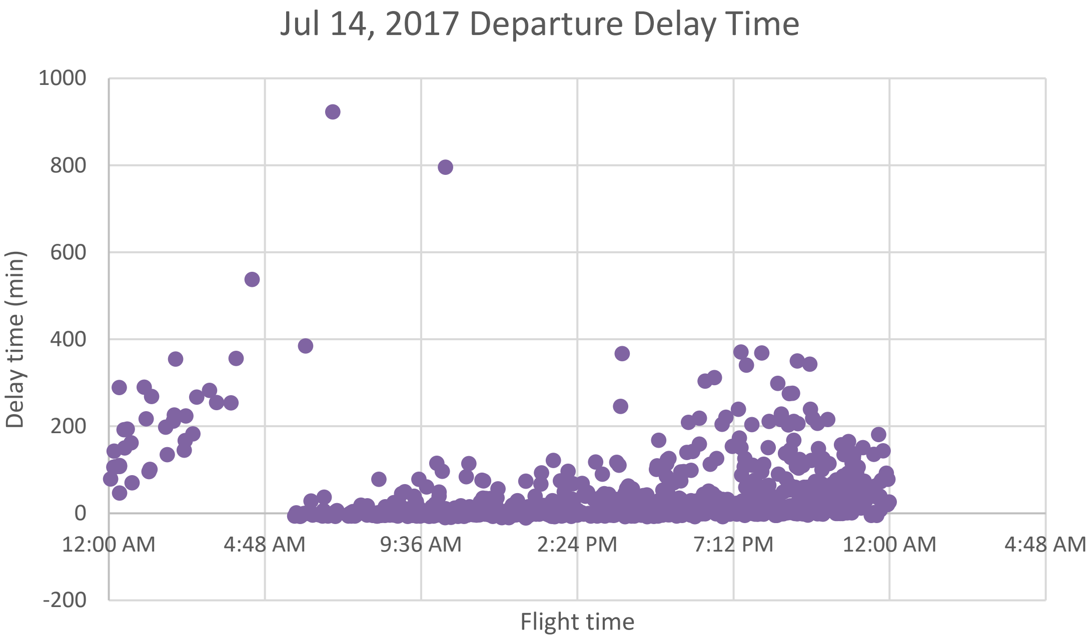


Figure 6-43 Departure Delay Time on Friday, July 14, 2017

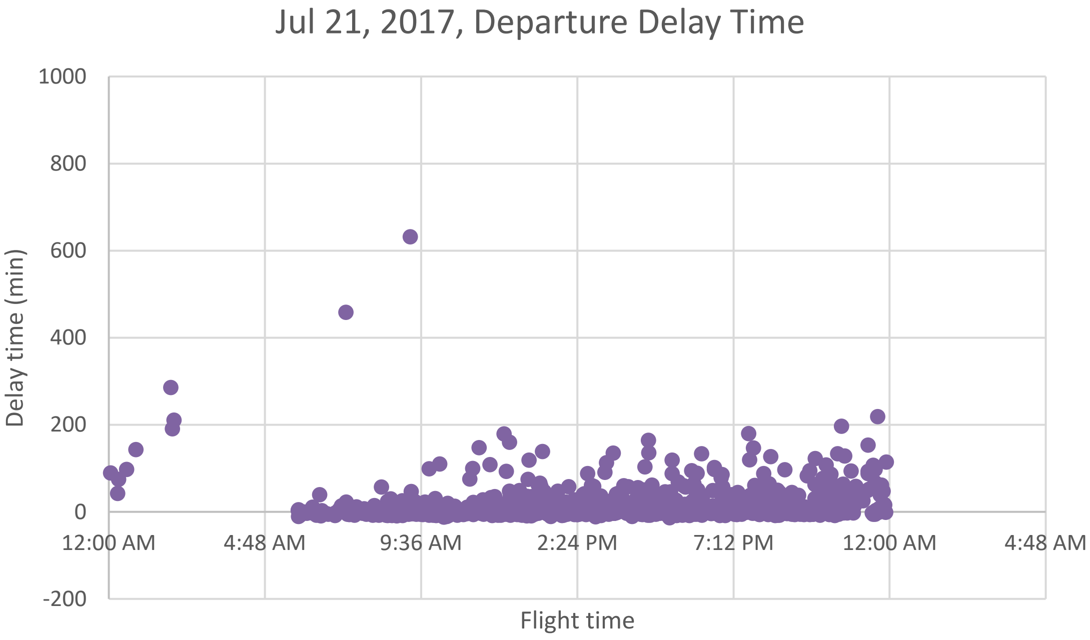


Figure 6-44 Departure Delay Time on Friday, July 14, 2017

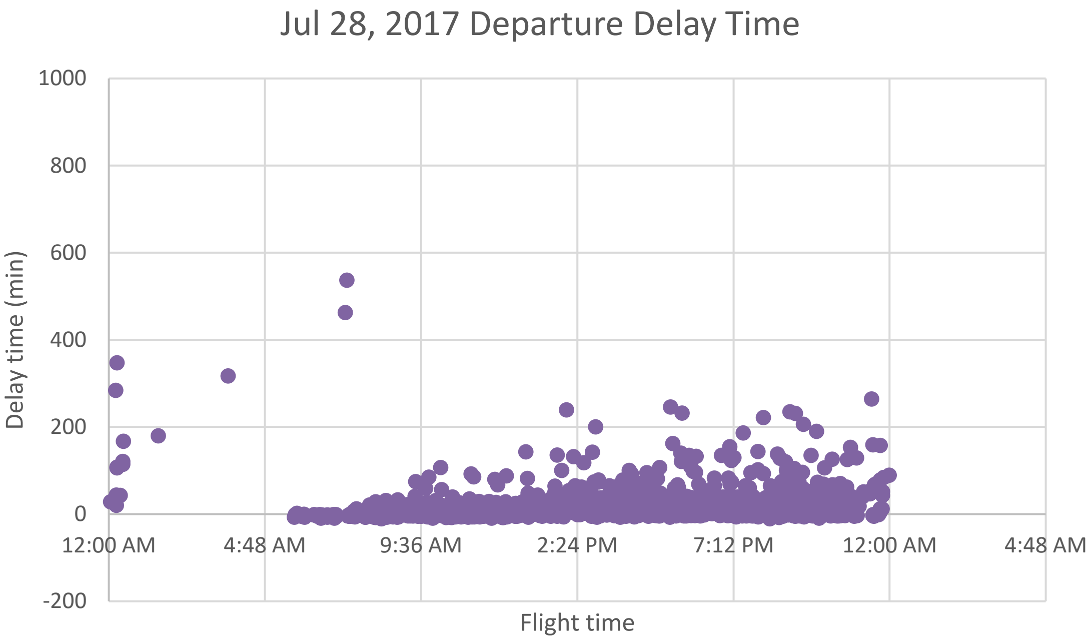


Figure 6-45 Departure Delay Time on Friday, July 28, 2017

6.5.2 Delay Reason

There are five categories that explaining the factors leading to flight delays. Those are reported by airlines to the Bureau of Transportation Statistics.

- Air Carrier Delay
  - Crew problems
  - Ground activities
- Extreme Weather Delay
  - Tornado
  - Blizzard
  - Hurricane or any significant meteorological conditions
- National Aviation System (NAS) Delay

    - Non-extreme weather conditions
    - Airport operations
    - Heavy traffic volume
    - Air traffic control
- Late-arriving Aircraft Delay
    - Delay from a previous flight
- Security Delay
    - Evacuation of terminal and re-boarding of aircraft due to a security breach

Figure 6-46, 6-47, 6-48, and 6-49 illustrate the factors leading to flight delays. The outliers usually result from the air carrier delay.

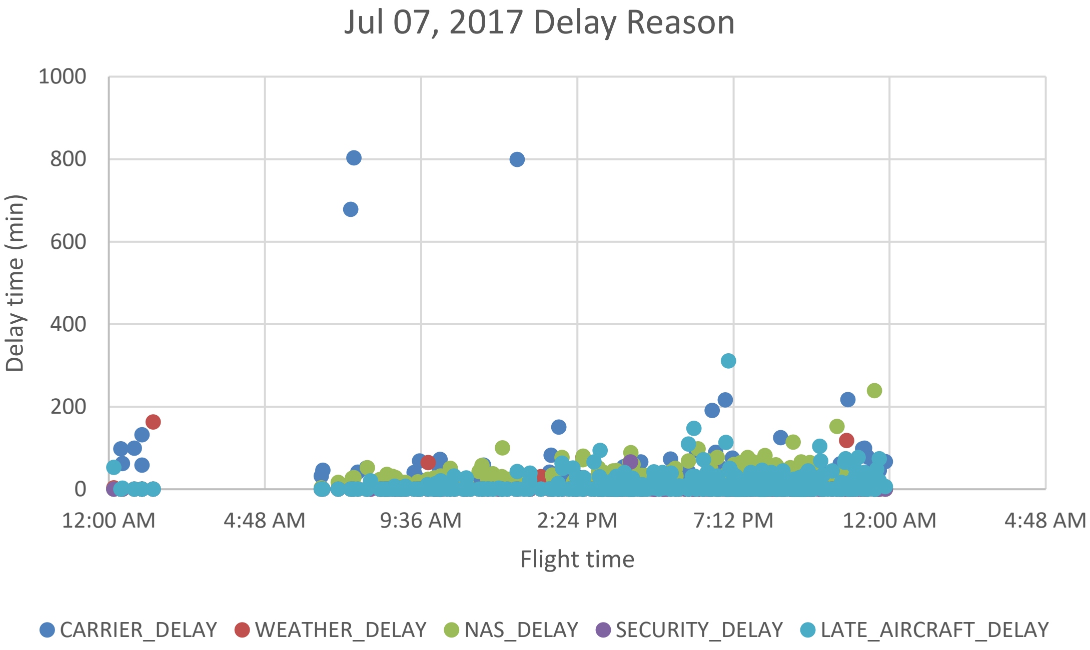


Figure 6-46 Delay Reason Analysis on Friday, July 07, 2017

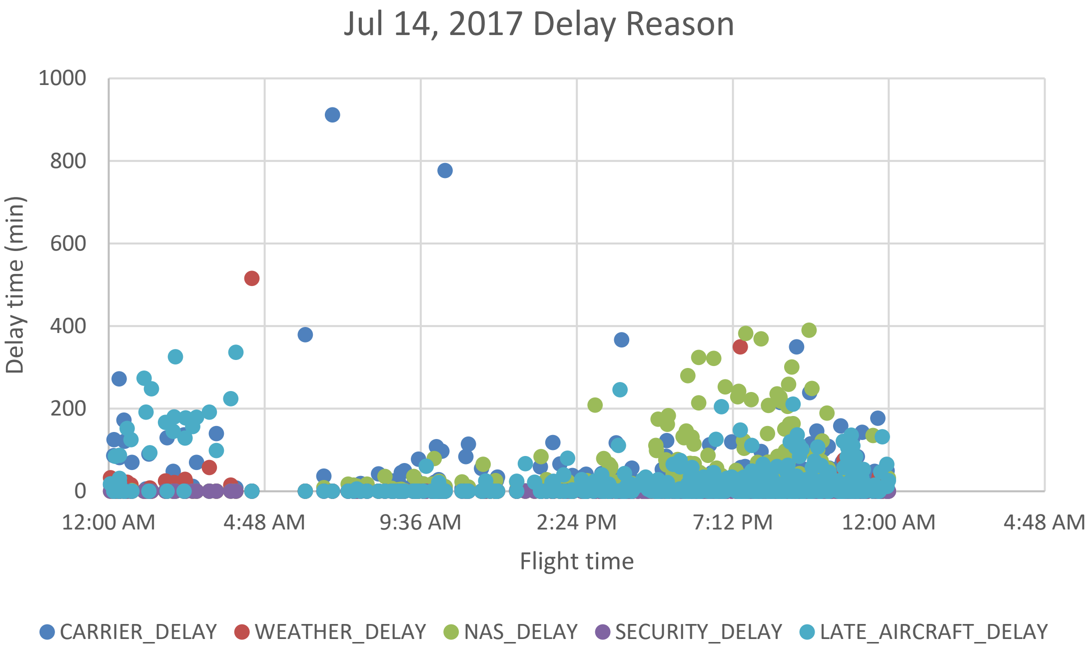


Figure 6-47 Delay Reason Analysis on Friday, July 14, 2017

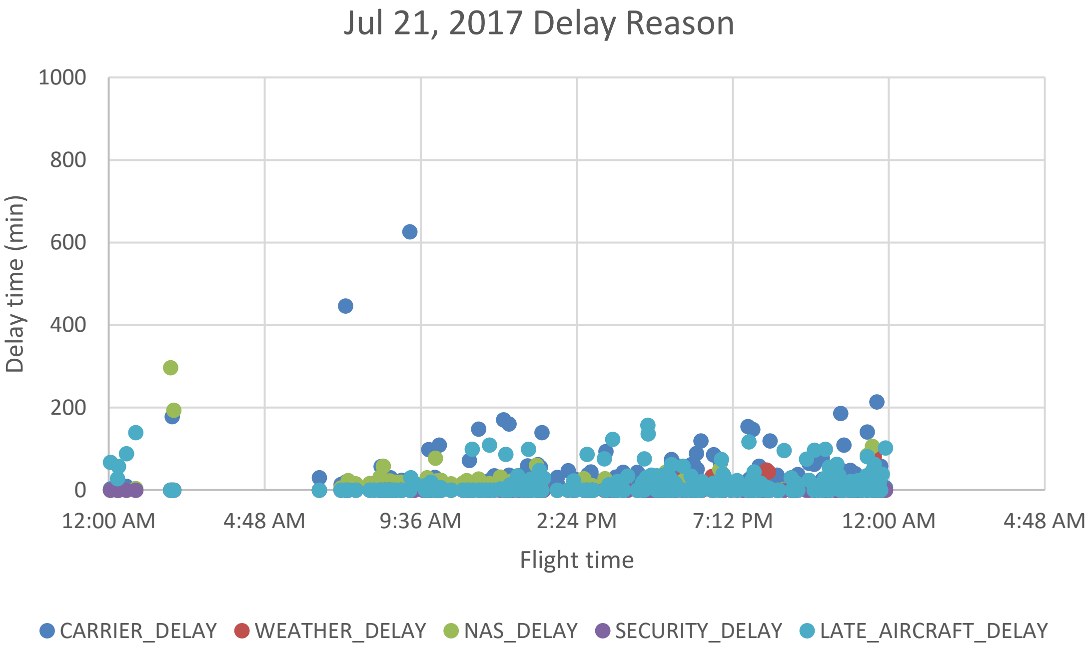


Figure 6-48 Delay Reason Analysis on Friday, July 21, 2017

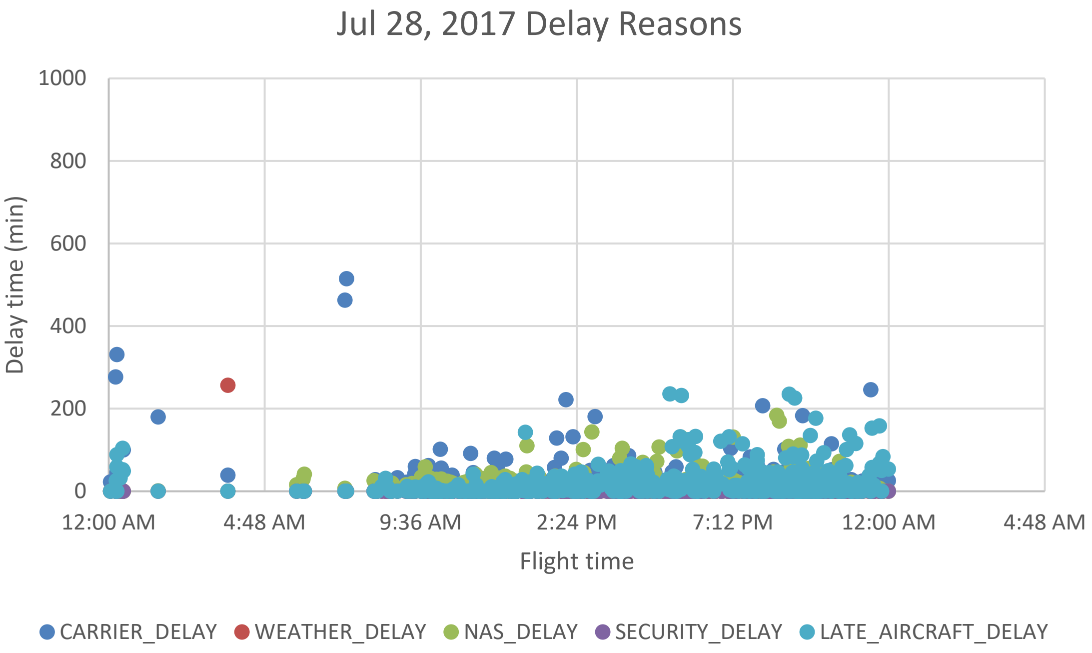


Figure 6-49 Delay Reason Analysis on Friday, July 28, 2017

However, the simulation modeling process is not dealing with all delay categories. It only treats weather delay, heavy traffic delay, airport operational delay, and ground handling delay. Thus, the categories that are not dealing with in the simulation should be excluded for more reliable validation.

Figure 6-50, 6-51, 6-52 and 6-53 illustrate the selected delay reasons after filtering. They treat 'Air Carrier Delay,' 'Weather Delay,' and 'NAS Delay.'

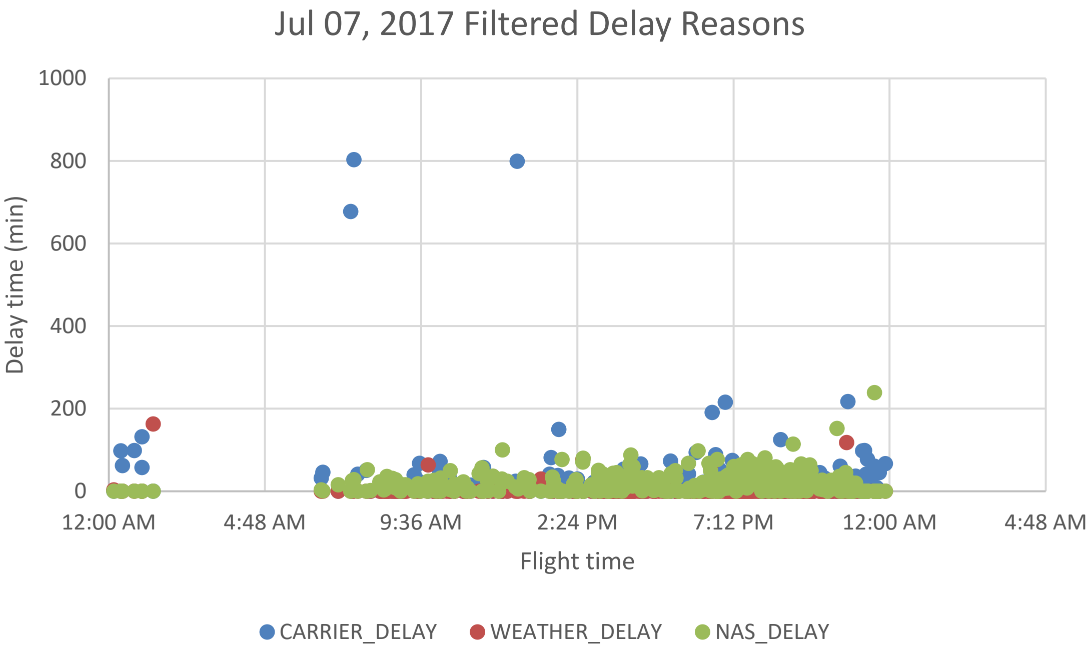


Figure 6-50 Selected Delay Reason on Friday, July 07, 2017

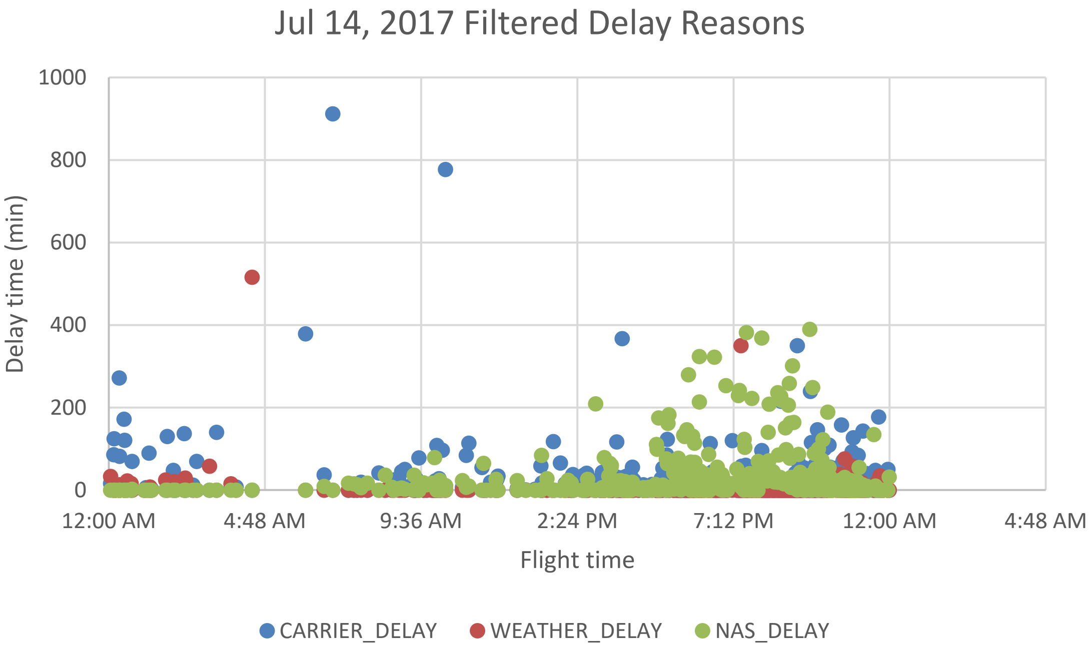


Figure 6-51 Selected Delay Reason on Friday, July 14, 2017

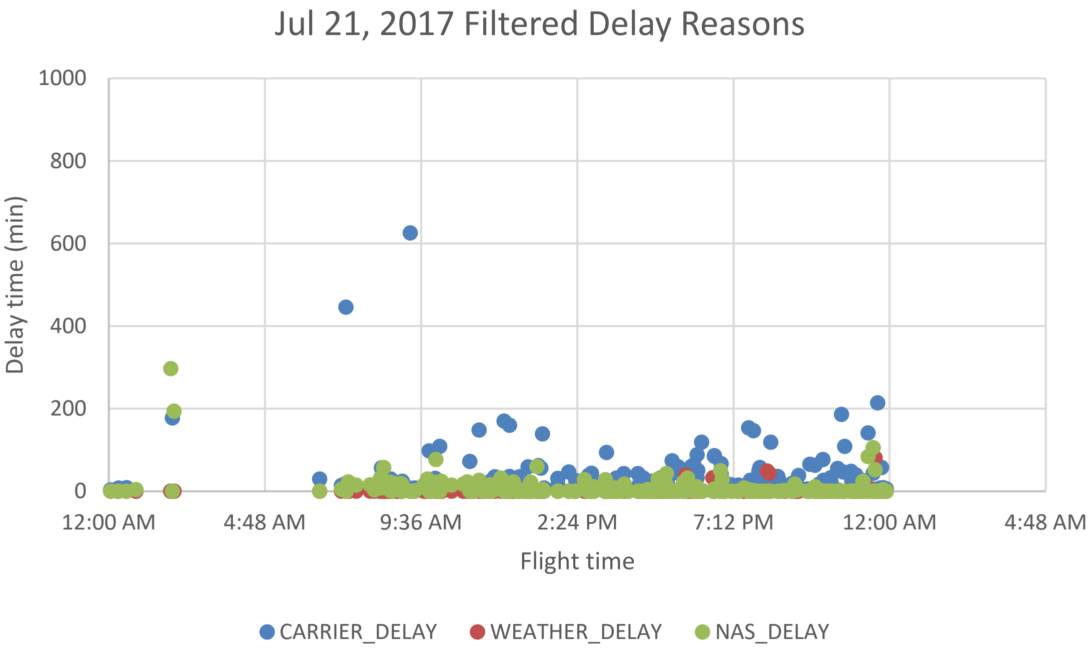


Figure 6-52 Selected Delay Reason on Friday, July 21, 2017

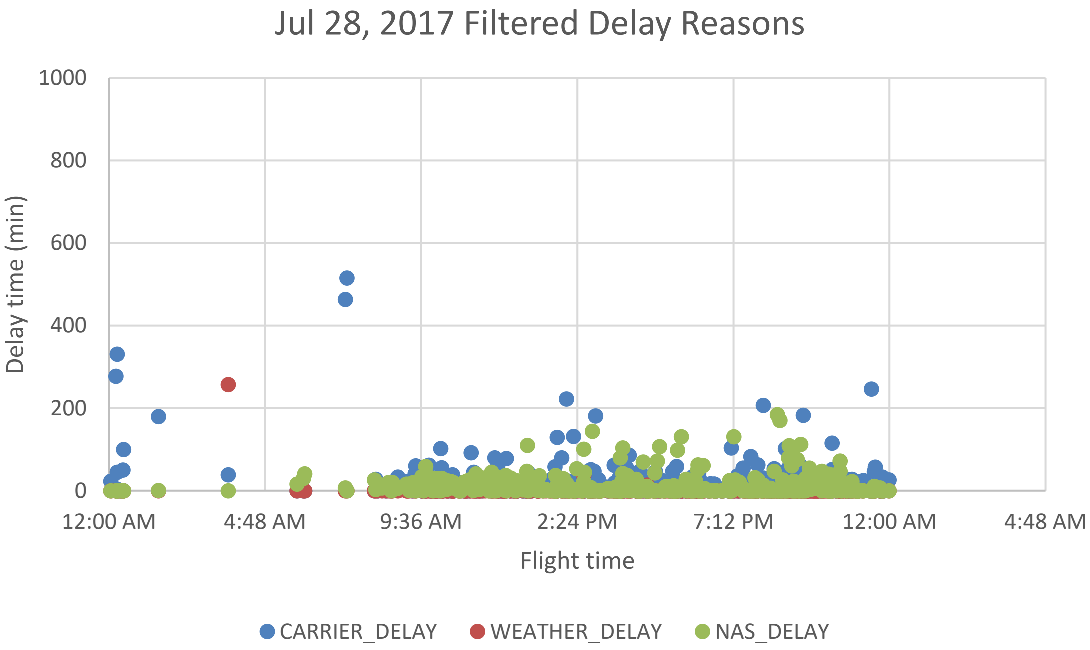


Figure 6-53 Selected Delay Reason on Friday, July 28, 2017

6.5.3 Comparison

Figure 6-54 illustrates the histogram of delay time. It tracked all flights in a day and counted the number of flights per each size of delay time. The column shows the performance of simulator, and the lines illustrate the records of actual system. The performance of simulator comes from 47 resources (See Section 7.2) and zero schedule variability buffer. All distributions peaked at $[15, 20)$ so that those are a right-skewed distribution. Figure 6-54 demonstrates that the actual system has a longer tail than the simulation. The simulation shows more truncated distribution than the actual system.

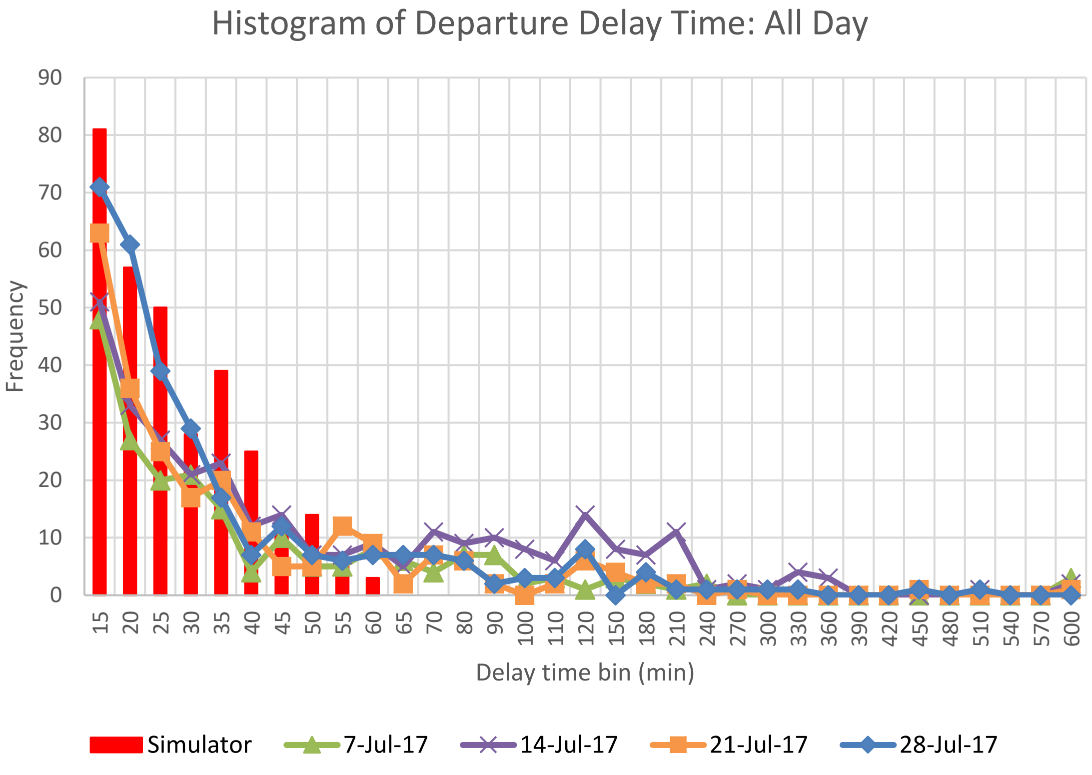


Figure 6-54 Distribution of Number of Flights: All Day

Figure 6-54 shows the whole day comparison, but it does not an impartial observation. The actual system has tracked all flight continuously, thus the midnight flight has been impacted from the flights of the night before. However, the simulation starts from 00:00 AM so there is no impact from the night before.

Therefore, the comparison will proceed only in the evening because the evening can be affected from the morning or the afternoon if there is any unusual incident. Figure 6-55 illustrates the histogram of delay time in the evening. It tracked all flights after 6 pm and counted the number of flights per each size of delay time. The column shows the performance of simulator, and the lines show the records of actual system. All lines peaked at $[15, 20)$ so that those are a right-skewed distribution. However, the column does not show an explicit peak. Figure 6-55 shows that the actual system has a longer tail than the simulation.

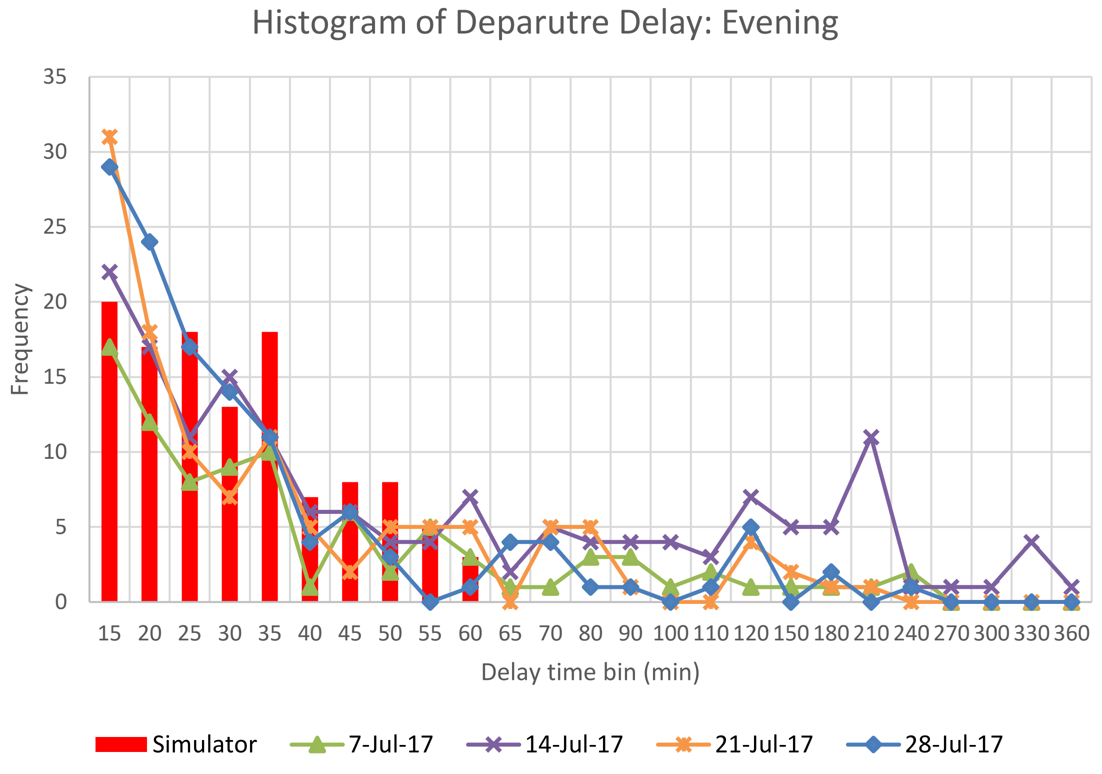


Figure 6-55 Distribution of Number of Flights: Evening

Table 6-40 and 6-41 captured the metrics to compare. Table 6-40 shows the results of all day and table 6-41 shows the results of evening time.

Table 6-40 Statistical Analysis: All day

	Average Delay Time (min)	1st Quartile and Median Delay Time (min)	Number of Delayed Flights	Total Delay Time (min)	Standard Deviation
Simulator	29.08	19 and 26	314	9130	11.22
7-Jul-17	55.81	20 and 31	204	11385	95.48
14-Jul-17	76.75	24 and 39	307	23563	100.50
21-Jul-17	47.21	19 and 29	239	11282	61.54
28-Jul-17	45.29	20 and 27	303	13723	58.15

Table 6-41 Statistical Analysis: Evening

	Average Delay Time (min)	1st Quartile and Median Delay Time (min)	Number of Delayed Flights	Total Delay Time (min)	Standard Deviation
Simulator	32.79	22 and 30	117	3835.9	12.48
7-Jul-17	50.47	22 and 32	90	4542	48.13
14-Jul-17	81.17	25 and 42	161	13068	82.96
21-Jul-17	43.67	19 and 30	118	5155	38.33
28-Jul-17	40.27	21 and 28	128	5154	38.32

Table 6-40 and 6-41 demonstrate that the simulator has more delayed flights than the actual system slightly; however, it has less total and average delay time regardless of previous flights. The simulator shows better performance, thus it looks superior to the actual system based on the values. However, there are uncaptured delay reasons on actual data analysis.

To compare the simulation to the actual system, section 6.5.2 discussed that filtering the causes of delay. The actual system and simulator handle the weather delay completely, but the simulator does not capture the delay from crew problems and air traffic control. Therefore, the validation has been processed partially, not completely. If the specific delay causes are revealed, then filtering the delay will work sufficiently. Thus, the complete validation will be available further.

CHAPTER 7. COST EVALUATION

The experimental results and their analysis have been discussed in chapter 6. Before showing the experimental results, chapter 6 reviewed the key components of experiments and explained the boundary condition definition for each variable: the number of resources and the schedule variability buffer. Then, chapter 6 illustrated the experimental results and evaluated their performance. In accordance with this, both sections estimated the hypotheses, which contribute to form the research.

In terms of the hypotheses, the experimental results implied that hypothesis 1, hypothesis 3, and hypothesis 3-1 are substantiated. Thus, as a further step, this chapter will derive a more stable solution with the simulator and explain how to utilize this. It will take the view of total delay time, the number of delayed flights, and associated operating costs.

For the stable solution, two variables are discussed here: the real case of the resources and the robust case for the schedule variability buffer.

7.1 Number of Resources: Real Case

The real case of the number of resources means greater than the minimum number of resources and fewer than the maximum number of resources.

- Real case:

$$\text{Worst case}(=25) < \text{Number of resources} < \text{Best case }(=\text{unlimited})$$

Here, the minimum has been defined as 25, and the maximum has been defined as infinite. The purpose of the sensitivity analysis will suggest a legitimate solution for the real case.

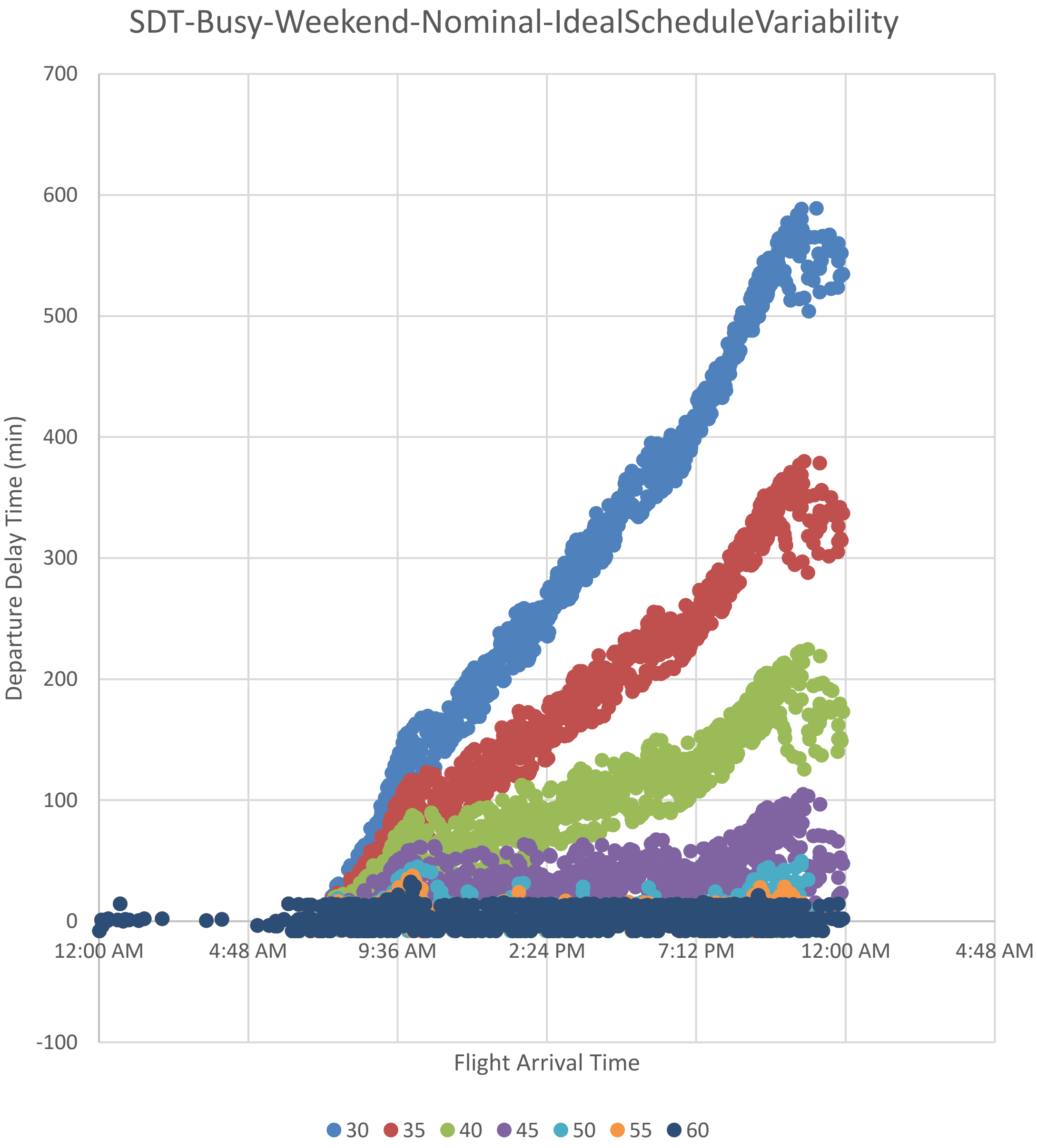


Figure 7-1 Departure Delay Distribution by the Number of Resources from 30 to 60

Figure 7-1 shows the departure delay time when the simulation ran each number of resources respectively. The representative arrival time is selected to match a weekend during the busy season as this presents the situation with the greatest amount of traffic. The flights operate under nominal weather conditions with the schedule variability buffer set to zero, indicating an ideal case.

Each number means the assigned number of resources for all ground handling activities. The more resources involved, the less the change in the departure delay time illustrated at the end of the day. This means that the return on an initial investment can be enormous.

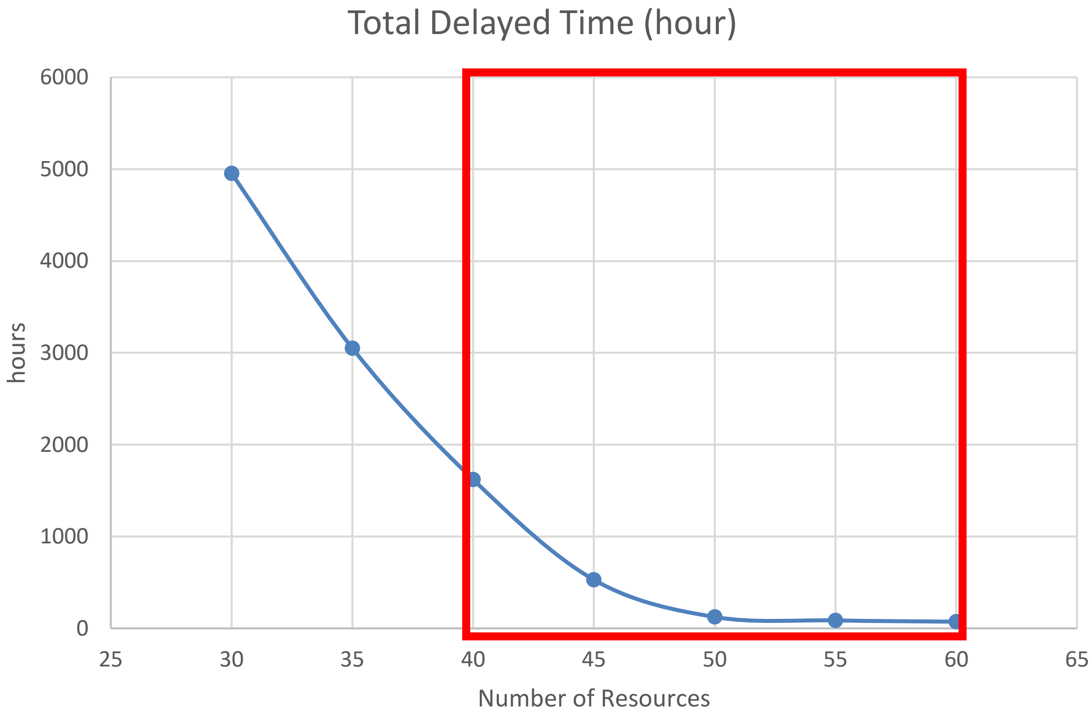


Figure 7-2 Total Delay Time by the Number of Resources

Figure 7-2 shows the total delay time (hours) for each of the resource availability conditions considered before. From 30 resources to 40 resources, there is a significant reduction of cumulative delay time. Thus, it is recommended to install more resources than 40.

However, this assumes that the cost of installation is identical regardless of the type of activity. It is accessible to the number of resources required for each activity, but not for the cost of installation of these resources.

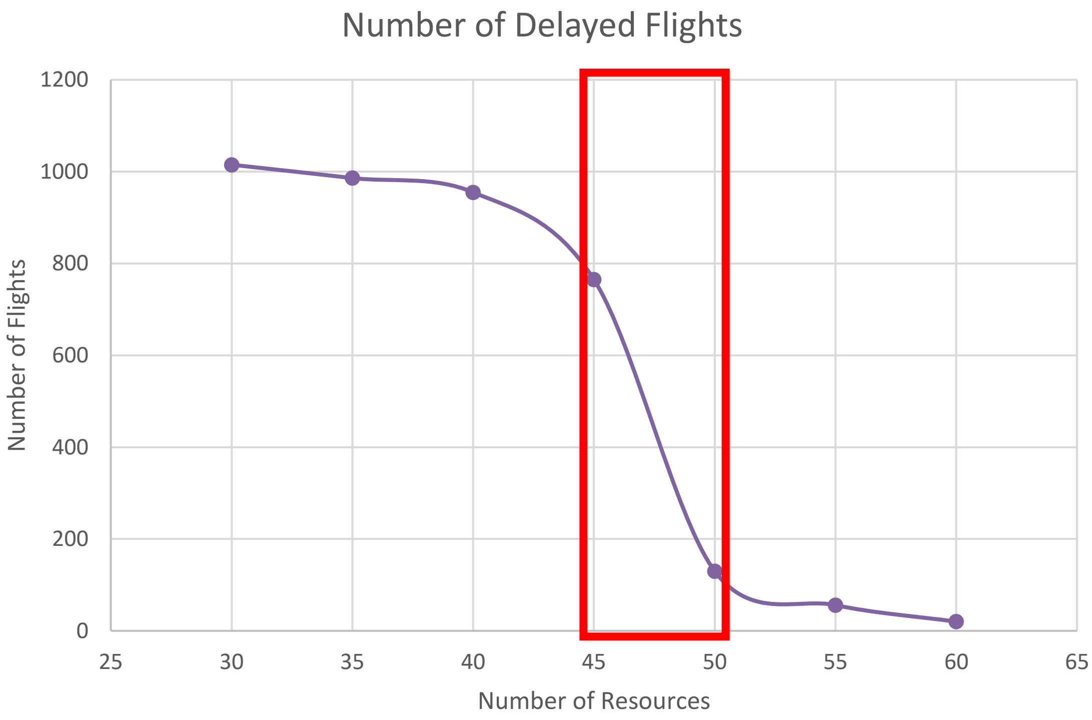


Figure 7-3 Number of Delayed Flights by the Number of Resources

Figure 7-3 illustrates the number of delayed flights as a function of the number of resources. The most significant portion is from 45 resources to 50 resources. Due to this large reduction, this portion is further explored.

Table 7-1 specifies the total delay time (hours), the average delay time per flight (minutes), and the number of delayed flights for each number of available resources. Total delay time counts all delayed flights, including those with delays of less than 15 minutes.

Table 7-1 Delay Time and Number of Delayed Flights by Number of Resources

Number of Resources	Total Delay Time (hour)	Mean Delay Time per Flight (min)	Number of Delayed Flights
30	4953.65	265.61	1015
35	3050.03	163.54	986
40	1620.93	86.91	955
45	529.01	28.36	765
50	124.01	6.65	130
55	86.72	4.65	56
60	72.52	3.89	20

In terms of the total delay time, this data suggests that 45 resources should be marked. However, when reviewed with respect to the number of delayed flights, 50 resources should be marked. Therefore, the range of 44 to 51 available resources will be further explored.

Figure 7-4 contains the departure delay time by the number of resources in the range of 44 to 51. The applied arrival scenario is similar to before, representing a weekend during a busy season under nominal weather conditions. For the schedule variability buffer, the ideal case is entered.

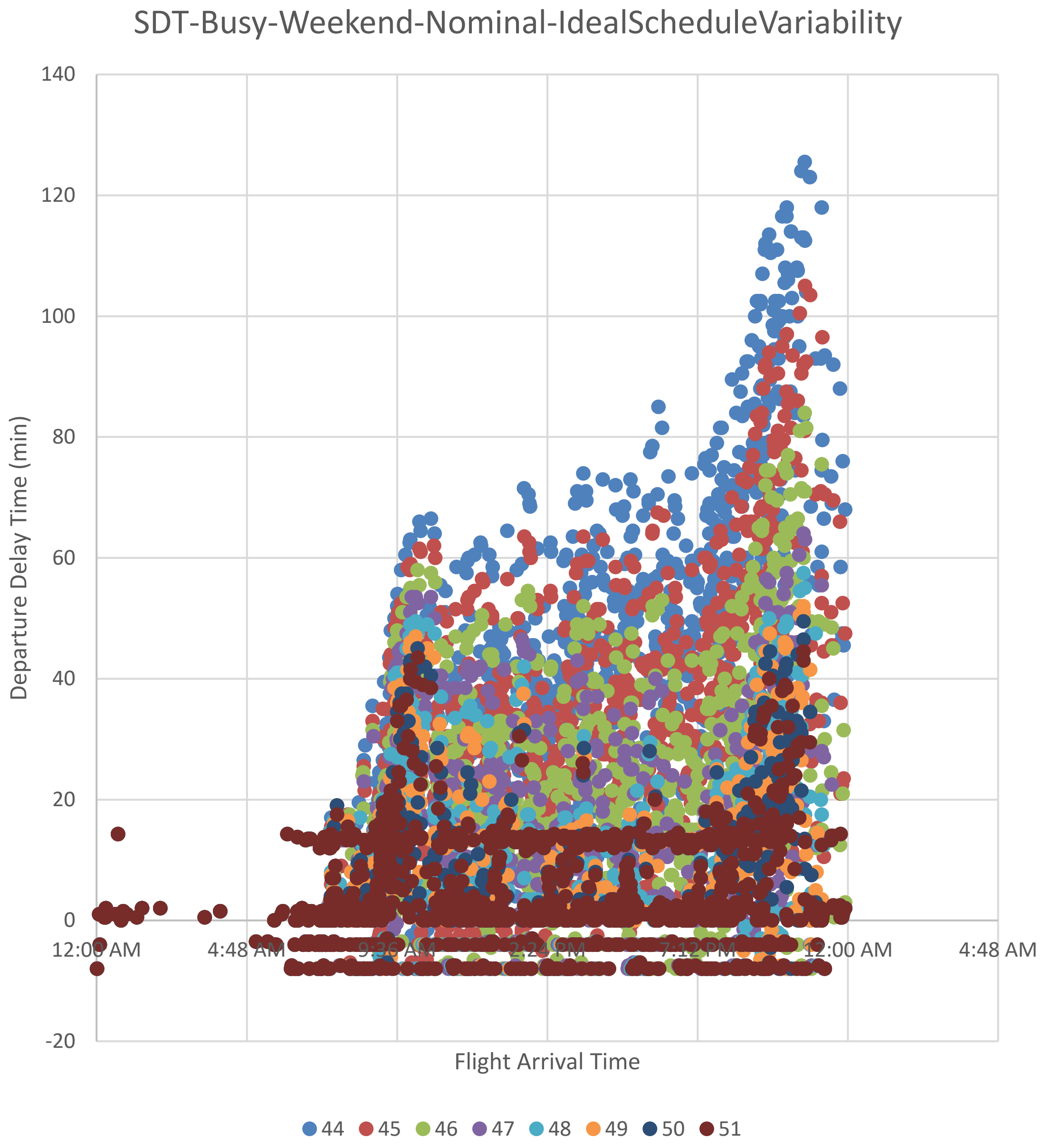


Figure 7-4 Departure Delay Distribution by the Number of Resources from 44 to 51

The longest delay time is recorded as 124 minutes, but most of the departure delay times are less than 80 minutes. The fifty-one resources' plot exhibits a multi-modal shape distribution: one peak for morning and another peak for the afternoon.

The critical metrics are also tracked: the total delay time and the number of delayed flights. Figure 7-5 shows those metrics and mean delay time per flight.

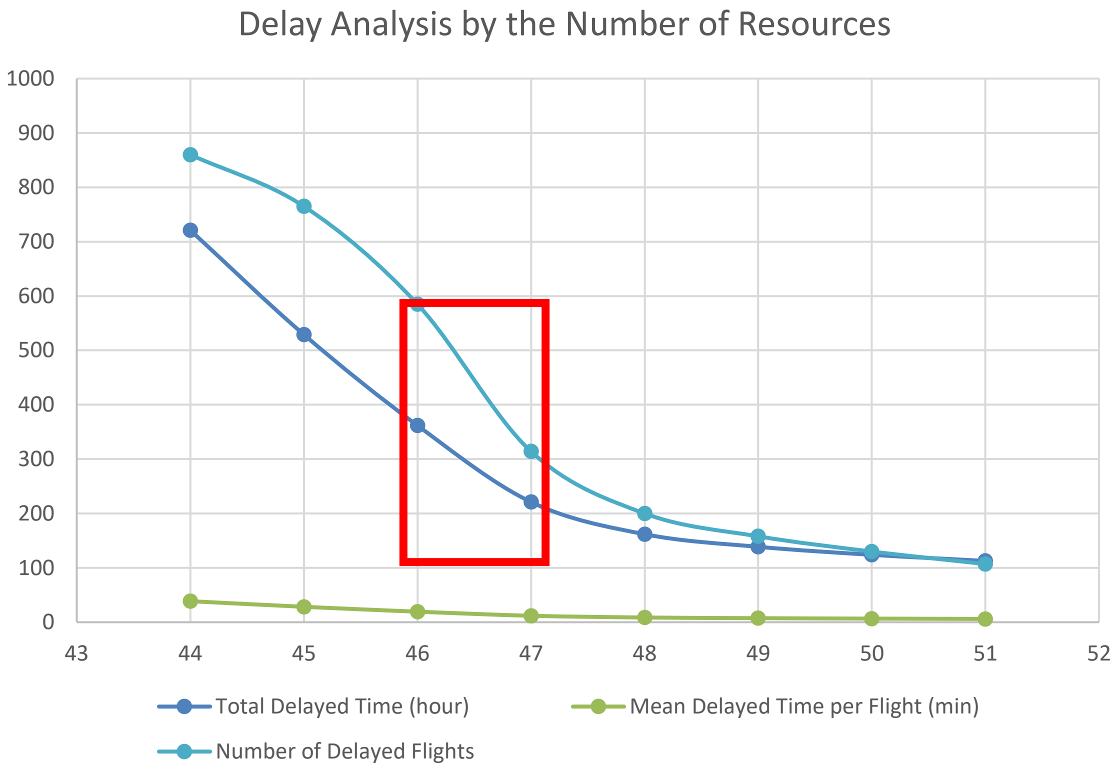


Figure 7-5 Delay Analysis by the Number of Resources from 44 to 51

In terms of the number of delayed flights, it was found that by increasing the number of resources, there is a sharp decrease in flight delays from 46 to 47. This suggests that by adding a single resource to an active group of 46 resources an airline company has the potential to eliminate about 300 flights delays, making this a promising investment.

From the view of total delay time, 47 is a recommended number of resources if considering delta as a core motivator. To get reliable solutions for the number of resources, Table 7-2 indicates the total delay time (hour), the average delay time per flight (minute), and the number of delayed flights by the number of resources.

Table 7-2 Delay Time and Number of Delayed Flights by Number of Resources

Number of Resources	Total Delay Time (hour)	Mean Delay Time per Flight (min)	Number of Delayed Flight
44	721.09	38.66	860
45	529.01	28.36	765
46	361.85	19.4	585
47	221.11	11.86	314
48	161.85	8.68	200
49	138.7	7.44	158
50	124.01	6.65	130
51	112.72	6.04	107

Regarding the mean delay time per flight, 47 resources are recommended. Therefore, the suggested value of resources for the busy season's weekend traffic is recommended at 47 as a real case scenario.

7.2 Schedule Variability Buffer: Robust Case

The robust case of the schedule variability buffer has a boundary condition: more than the zero buffer time (Ideal case) and less than the maximum buffer time (Largest case)

- Robust

$$\text{Ideal case } (= 0) < \text{ Schedule variability buffer } < \text{ Largest case } (= \max)$$

The schedule variability buffer is derived from the largest case based on the historical data of the early arrival time (See section 6.2.2). It assumes a linear increase because the aircraft, which requires a longer turnaround time, has a more potent factor to disturb the turnaround process than the shorter one. Thus, the robust case should follow this assumption.

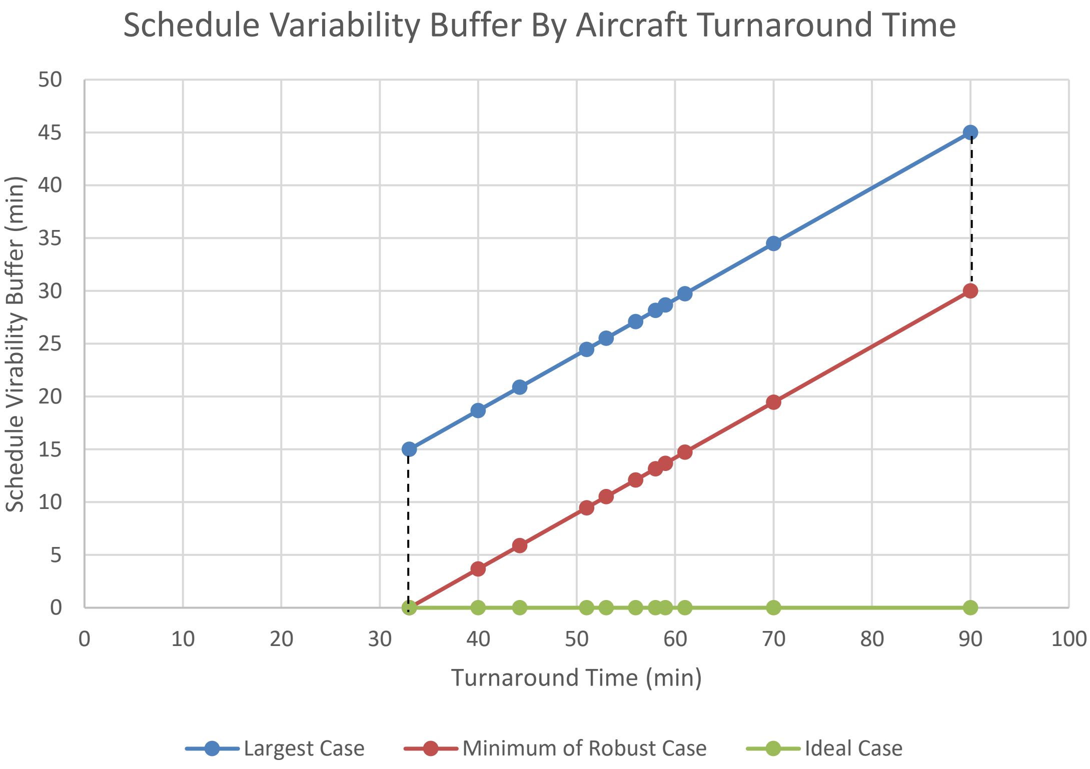


Figure 7-6 Schedule Variability Buffer: Ideal, Largest and Robust Cases

Figure 7-6 indicates the open region which the robust case may occupy. The red line represents the minimum of the robust case. The largest case plays acts as an asymptote for the robust case. Therefore, the region from the minimum of the robust case to the largest case is excluded.

Here is the definition of the robust case:

$$y = 0.526x - b$$

$$-17.37 \leq b < -2.37$$

$$\rightarrow 30 \leq y_{max} < 45$$

y shows the schedule variability buffer of the aircraft model, and x is the turnaround time of the aircraft model (unit: minutes). y_{max} is the maximum value of each schedule variability buffer. For example, y_{max} of the largest schedule variability buffer is 45.

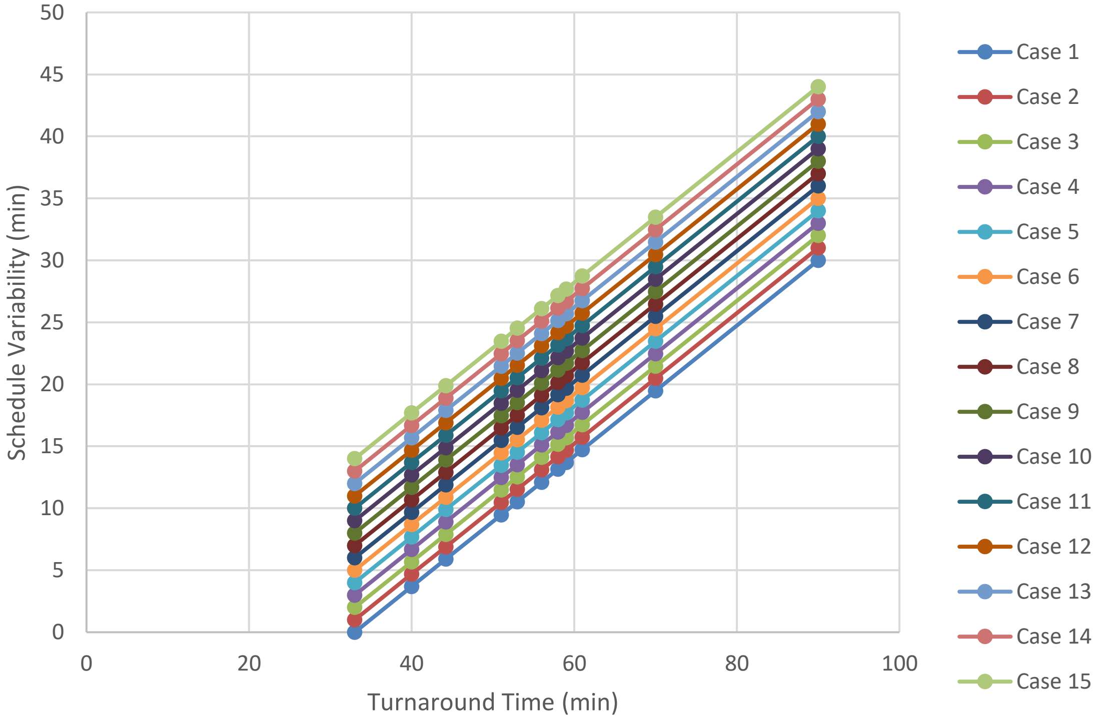


Figure 7-7 Candidate of Robust Schedule Variability Buffer

Figure 7-7 shows the candidates for the robust schedule variability buffer. Since the integer y_{max} is only considered, there are a total of 15 cases. Each case and its total delay time will be used for the cost calculation in the next section.

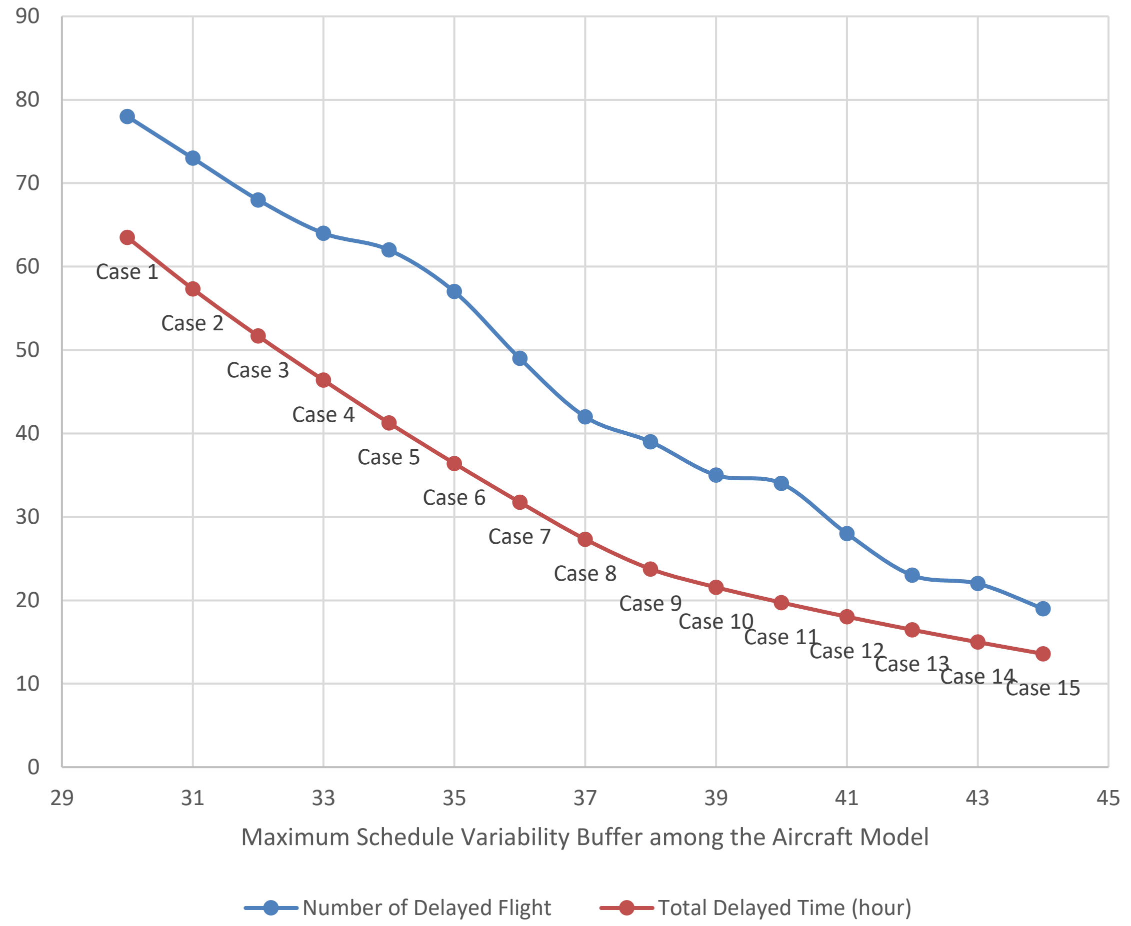


Figure 7-8 Delay Evaluation by the Schedule Variability Buffer

Figure 7-8 illustrates the number of delayed flights and the total delay time for each candidate. This total delay time record will be part of the cost calculation. Regarding the number of delayed flights, there is a steep decline from case 6 to case 8. However, there is no sharp decline in the total delay time when tracking changes in the amount.

7.3 Cost Analysis

Section 7.1 derived the suggested number of resources based on the volume of traffic. Using this, section 7.2 discussed how to find the range of the robust schedule variability buffer.

As explained, the schedule variability buffer plays the role of buffer time, embedded into the schedule as a warning for future delays. The robust schedule variability buffer is derived from minimizing the cost due to scheduling it. The overall system cost is a summation of the flight delay costs and additional scheduling cost. The additional scheduling cost stems from the extra cost which results from the change of the turnaround time.

$$C_{system} = C_{delay,TA} + C_{schedule}$$

The mean cost of aircraft block time for U.S. airlines was $68.48 per minute in 2017 [83]. It consists of flight attendants, staff, fuel, maintenance, aircraft ownership, and other aeronautical costs. Here, the objective is tracking the delay on the turnaround process and estimating its economic impact. Thus, the fuel cost will be excluded.

Flight delays require the extra ground staffs and gates, and impose costs on airline passengers and shippers because of the form of lost productivity [83]. There is no access to the ground cost of Atlanta Hartsfield Airport. Thus, the airport excess parking fee of Melbourne airport is used instead. This can be accessed in [82], and shows costs in Australian Dollars in 2007. Thus, these values were transferred to US dollars, considering US inflation. Based on the Federal Aviation Administration-recommended values as adjusted using the Bureau of Labor Statistics employment cost index, the average value of a passenger’s time is defined as $49 per hour.

Table 7-3 shows the direct aircraft operating cost per block minute for each category.

Table 7-3 Average Cost of Aircraft Block Time

Category	Direct Aircraft Operating Cost per Block Minute
Crew: Pilots/Flight Attendants/Staffs (C_{crew})	\$22.67
Maintenance ($C_{maintenance}$)	\$12.37
Aircraft Ownership ($C_{ACownership}$)	\$9.4
Ground (C_{ground})	\$1.87
Customer Compensation ($C_{customer}$)	\$0.82
Other Aeronautical Cost (C_{other})	\$2.77

The total cost from delay is defined here:

$$C_{delay,TA} =$$

$$T_{delay,TA} * \{(C_{crew} + C_{maintenance} + C_{ACownership} + C_{ground} + C_{other}) + (C_{customer} * Number\ of\ Passengers)\}$$

, where $T_{delay,TA} = \text{the total dealyed time from a turnaround process}$

Table 7-4 shows the result of the cost calculation based on table 7-3. It illustrates the delay cost when each schedule variability buffer is applied. With the exception of passenger compensation, all positive delay time is considered in the calculation of delay cost. Passenger compensation is only considered if the delay time is greater than 60 minutes. Only the ideal case imposes the cost of passenger compensation.

Table 7-4 Delay Cost by the Schedule Variability Buffer

Schedule Variability Buffer	Delay Time (min)	Delay Cost
Case 0 (Ideal)	13266.9	$730,540.46
Case 1	3810.11	$187,000.23
Case 2	3439.85	$168,827.72
Case 3	3100.56	$152,175.39
Case 4	2783.01	$136,589.91
Case 5	2475.95	$121,519.77
Case 6	2184.66	$107,223.28
Case 7	1905.30	$93,511.88
Case 8	1639.27	$80,455.31
Case 9	1425.34	$69,955.53
Case 10	1293.8	$63,499.70
Case 11	1184.06	$58,113.82
Case 12	1082.24	$53,116.18
Case 13	987.82	$48,482.00
Case 14	899.29	$44,137.13
Case 15	815	$40,000.20
Case 16 (Largest)	734.79	$36,063.47

The results in the table show that as the schedule variability buffer time increases, the total delay time and the cost due to the delay decrease. In particular, there is a considerable gap depending on the existence of the schedule variability buffer.

The traditional way to handle the buffer time is to allocate the same amount time to all flights. Then, to analyze its economic impact, the scheduling cost is linearly increased proportionally to the buffer time.

However, this research handles the buffer in different way: increasing linearly by aircraft model. Thus, due to the inconsistency among the flights, the additional scheduling cost is calculated for each aircraft model.

The scheduling cost consists of flight attendants, staff, fuel, maintenance, aircraft ownership, ground, insurance, and other aeronautical costs. As before, the fuel costs are excluded here.

$$C_{scheduling} = C_{crew} + C_{maintenance} + C_{ACownership} + C_{ground} + C_{insurance} + C_{other}$$

Table 7-5 shows the cost per block hour (US$) for each aircraft model included in the simulation. Each entry shows the average value of the reported operating cost from the following airlines: Alaska, Allegiant, American, Delta, Frontier, Hawaiian, JetBlue, Miami Air, Southwest, Spirit, Sun Country, United, US Airways, and Virgin America. It is accessible through the website: www.planestats.com

Due to insufficient data for A350-1000 and A380, A350 takes the equal value of B747-400. A380 is the largest model considered. Thus it takes the highest value of B747-400.

Table 7-5 Aircraft Model: Cost per Block Minute

Aircraft	Crew	Ground	AC ownership	Maintenance	Insurance	Other
B737-600	$20.1	$1.87	$17.82	$22.25	$0.67	$1.55
B737-700	$12.82	$1.87	$9.45	$11.98	$0.13	$0.95
A320-200, NEO	$11.08	$1.87	$11.05	$11.20	$0.23	$1.92
B787-9	$32.68	$1.87	$10.87	$20.25	$0.08	$7.67
A330-200,800	$26.02	$1.87	$16.25	$22.75	$0.13	$1.07
B787-10	$39.53	$1.87	$12.95	$25.97	$0.05	$8.07
B777-300ER	$42.58	$1.87	$28.70	$38.33	$0.12	$2.50
A330-300,900	$30.78	$1.87	$13.15	$23.38	$0.07	$0.97
B747-400	$33.22	$1.87	$6.92	$23.93	$0.03	$21.02
A350-1000	$33.22	$1.87	$6.92	$23.93	$0.03	$21.02
A380	$35.17	$1.87	$3.27	$33.52	$0.02	$41.60

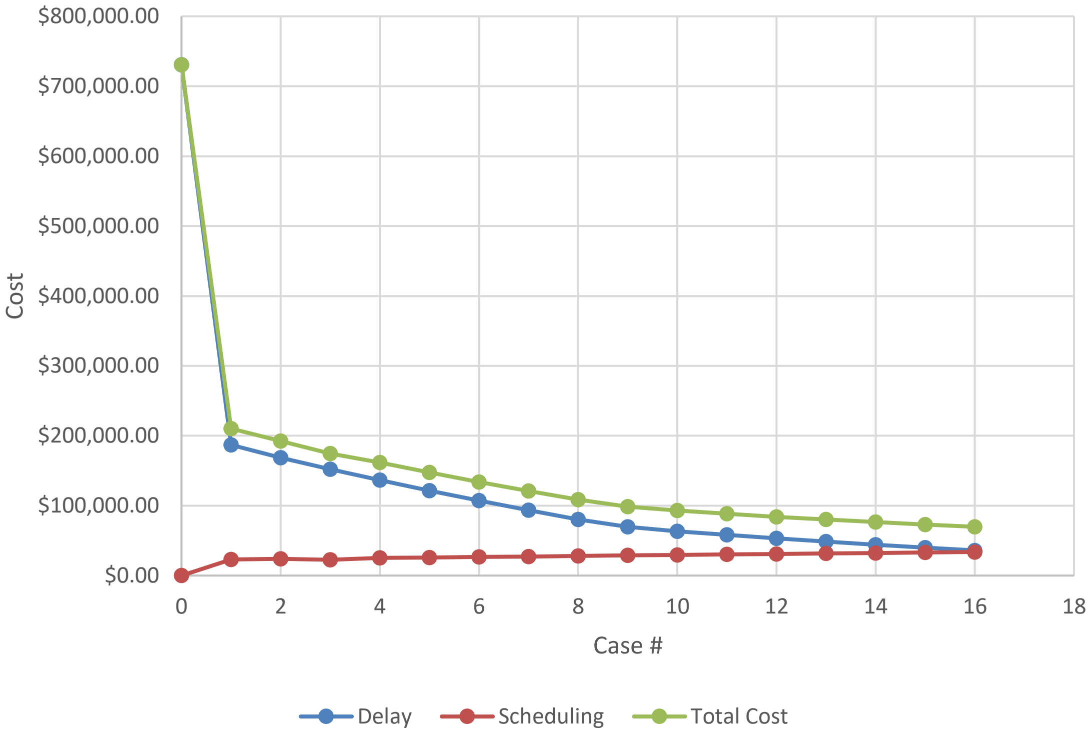


Figure 7-9 Cost Distribution: All Positive Delay Time

Figure 7-9 presents the cost of delay, the scheduling cost, and the total cost distribution. The x-axis indicates the case number and the y-axis indicates the cost. All delay times are recorded with the exception of negative delays, even when the delay time is less than 15 minutes. The case zero (Ideal schedule variability buffer) indicates that the initial cost of the schedule variability buffer contributes to a reduction of 70% of the initial total cost.

Total cost is dominated by the delay cost. In other words, the delay cost has the potential to reduce the total cost much more than the scheduling cost. Table 7-6 shows all specific values for each case.

Table 7-6 Overall System Cost with All Positive Delay Time

Schedule Variability Buffer	Delay Time (min)	Delay Cost	Scheduling Cost	Total
Case 0 (Ideal)	13266.9	$730,540.46	$0.00	$730,540.46
Case 1	3810.11	$187,000.23	$23,060.63	$210,060.86
Case 2	3439.85	$168,827.72	$23,774.23	$192,601.95
Case 3	3100.56	$152,175.39	$22,395.30	$174,570.69
Case 4	2783.01	$136,589.91	$25,201.43	$161,791.34
Case 5	2475.95	$121,519.77	$25,915.03	$147,434.80
Case 6	2184.66	$107,223.28	$26,628.63	$133,851.91
Case 7	1905.30	$93,511.88	$27,342.23	$120,854.11
Case 8	1639.27	$80,455.31	$28,055.83	$108,511.14
Case 9	1425.34	$69,955.53	$28,769.43	$98,724.96
Case 10	1293.8	$63,499.70	$29,483.03	$92,982.73
Case 11	1184.06	$58,113.82	$30,196.63	$88,310.45
Case 12	1082.24	$53,116.18	$30,910.23	$84,026.41
Case 13	987.82	$48,482.00	$31,623.83	$80,105.83
Case 14	899.29	$44,137.13	$32,337.43	$76,474.56
Case 15	815	$40,000.20	$33,051.03	$73,051.23
Case 16 (Largest)	734.79	$36,063.47	$33,764.63	$69,828.09

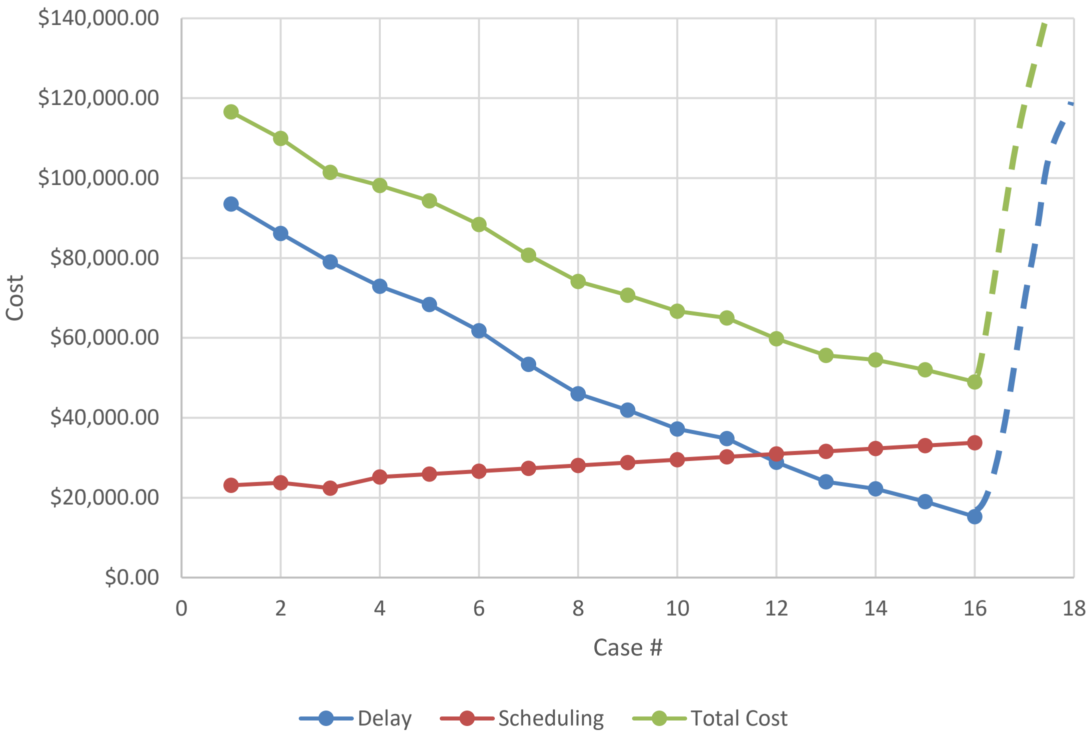


Figure 7-10 Cost Distribution: Delay Time > 15 minutes

Figure 7-10 presents the delay cost, the scheduling cost, and the total cost distribution if the delay time is exceeds 15 minutes. Case 0 is excluded in the figure due to its higher total cost, but it may be seen in table 7-7.

The lowest cost is shown with in Case 16, which has the maximum schedule variability buffer. This case assumes operation under the same number of aircraft. If the schedule variability buffer increases further, it will not be able to manage the schedule. In other words, purchasing the aircraft is required if the schedule variability buffer is set beyond that of Case 16.

The decreasing speed of the delay cost is faster than the increasing speed of the scheduling cost. The shape of the scheduling cost illustrates a flat function, thus the optimal cost is shown in the largest schedule variability buffer because the largest case contains the lowest delay cost.

Table 7-7 Overall System Cost with the Delays ≥ 15minutes

Schedule Variability Buffer	Delay Time (min)	Delay Cost	Scheduling Cost	Total
Case 0 (Ideal)	13266.9	$527,506.32	$0.00	$527,506.32
Case 1	3810.11	$93,487.07	$23,060.63	$116,547.70
Case 2	3439.85	$86,134.11	$23,774.23	$109,908.34
Case 3	3100.56	$79,044.63	$22,395.30	$101,439.93
Case 4	2783.01	$72,917.38	$25,201.43	$98,118.81
Case 5	2475.95	$68,358.11	$25,915.03	$94,273.14
Case 6	2184.66	$61,778.80	$26,628.63	$88,407.43
Case 7	1905.30	$53,369.33	$27,342.23	$80,711.56
Case 8	1639.27	$46,042.21	$28,055.83	$74,098.04
Case 9	1425.34	$41,919.49	$28,769.43	$70,688.92
Case 10	1293.8	$37,180.68	$29,483.03	$66,663.71
Case 11	1184.06	$34,774.47	$30,196.63	$64,971.10
Case 12	1082.24	$28,864.21	$30,910.23	$59,774.44
Case 13	987.82	$24,003.99	$31,623.83	$55,627.83
Case 14	899.29	$22,188.03	$32,337.43	$54,525.47
Case 15	815	$18,996.54	$33,051.03	$52,047.57
Case 16 (Largest)	734.79	$15,240.63	$33,764.63	$49,005.26

In comparison with the ideal schedule variability buffer, any cases with non-zero schedule variability buffer effectively reduce both the delay cost and the total cost. The overall system cost is taken from the summation of the delay cost and the additional scheduling cost. Based on the amount of data accessibly to the public, the overall cost is dominated by the delay cost. Even though the additional scheduling cost increases, the amount of decline driven by delay costs dominates. Therefore, the optimal cost is defined with the largest schedule variability buffer with the 47 resources condition. This solution exists for the busy season's weekend schedule.

7.4 Summary

Chapter 7 discussed how to derive the real case of resources and the range of the robust schedule variability buffer. Based on the derived resources, the candidate of the robust schedule variability buffer joined the calculation of direct operating cost. Since the concentration is a delay from the turnaround process and schedule to recover that delay, the fuel costs were excluded in the process.

Although there is a limitation of accessible data, the crucial variables are successfully tracked in the cost calculation process. In addition, it did not violate the core argument: the longer turnaround time requires a longer schedule variability buffer.

The minimal cost of the overall system is captured on the largest schedule variability buffer when proceeding with the busy season's weekend schedule. This indicates that the delay cost is more important to the reduction of the total cost.

CHAPTER 8. CONCLUSION

8.1 Overview

Due to high growth in demand for air travel, customers often experience congested airports. Improving the capacity of the air transportation system is almost impossible because of space and cost limitations. Thus, a more efficient operational strategy is necessary to handle the increased traffic with current facilities.

Although the ground handling process has significant impacts, it has not taken center stage in past and current research. Ground handling has an essential role in the recovery from past delays either aggravating or alleviating the problem. Additionally, based on previous records, the delay from the ground process is a critical cause of departure delay, affecting departure time by ten percent.

From the airline's perspective, inherent delay uncertainty has an adverse effect on their customers. Furthermore, increased congestion and delay produce significant financial inefficiencies. However, airlines recognize the saturation of airports, a factor that is not under their control [88]. Thus, airlines ought to attempt to ensure punctuality in the operation of ground handling to improve their service quality "On-time performance."

To alleviate the delay and emphasize the time efficiency of ground operations, the airlines could consider an innovative operational framework. The research work presented in the current dissertation has captured that the ground processes are an essential cause of departure delay and has explored strategies for improvement in the aircraft turnaround process such that little to no investment from the airlines would be required.

Here, the aim of the research focuses on improving the aircraft turnaround process with current capacity. It results in the question: how can we develop a stable operational approach to improve the turnaround process?

The aircraft turnaround process is a complex process. It is associated with multiple stakeholders and influenced by their actions. Thus, a key idea is how to integrate the actions of all relevant stakeholders. As a result, the critical improvement concept presented is the integration of work procedures including all stakeholders and management of relevant resources. It begs the next question: how can we integrate and test the concept?

Many researchers have adopted common types of closed-form analytical mathematical models to examine air traffic delay and congestion because such models are capable of providing several solutions simultaneously [39]. However, mathematical modeling may not be useful for large and complex problems [39]. Thus, for those problems, researchers have often relied on modeling and simulation techniques as a replacement. Simulation is the proper environment to test ‘what if?’ scenarios. It allows the users to test and better understand the system and alternative ways [84].

When considering the vast and complex airport environment, Discrete Event Simulation (DES) can be a suitable solution. DES allows us to do large scale simulations with computational efficiency [41], and includes the stochastic components and simulates a dynamic system based on a chronological sequence of events. For the systems featured by complex processes with infrastructure at a limited capacity, DES is often selected [44].

Aircraft turnaround process is a complicated and congested procedure with limited capacity. Airports, and specifically the turnaround process, are, therefore, ideally suitable for the application of such simulations because of their stochastic and dynamic characteristics [45]. From the practical perspective, a suitable model to simulate the turnaround process would be on that is able to model the operational uncertainties and investigate the operational activities with the required level of detail [46]. Therefore, the basic premise is that the use of DES to evaluate the proposed approach for airport operations.

To reduce the delay in the aircraft turnaround process, the DES methodology is selected. Then, for solid simulation modeling, the required inputs for the integration of the turnaround process within current physical capacity are defined. Thus, the historical flight data has been analyzed, and all turnaround activities and their time for the selected aircraft models have been discussed. Then, the operational scenarios are defined in two types: nominal and off-nominal.

A simulation of the turnaround process was created employing the input data and capturing multiple operational scenarios. It obeys a critical path by the sequence and dependency of the ground activities. In order to test the hypotheses, the simulator was set up as the apparatus for hypothesis testing.

In terms of the design of the experiment, the performance of simulator with the operational scenarios is discussed. The tracked metrics for delays and their impact are analyzed in the context of proving/disproving the previously stated hypotheses.

For example, the simulator has two operational strategies for decision-making: queuing the aircraft based on the Scheduled Departure Time (SDT) or First-Come-First-Served (FCFS). FCFS reflects how it is done today, and SDT is a suggested concept to make a more stable solution. Comparing the metrics (total delay time, and a number of delayed flights), SDT shows better performance in all cases. Thus, hypothesis testing is finished successfully.

The performance of the simulator proves the hypotheses and shows their reliability. Thus, based on the result, it calculates the direct operating cost under different scenarios. However, only the variables relevant to the turnaround process directly are evaluated. Even with limited access to the data, the relevant variables are tracked successfully in the cost calculation process. The minimal cost of the overall system is captured and indicates the dominant elements to reduce the total cost.

8.1.1 Proposed Concept

The proposed concept aims at the integration over the whole turnaround process within the current physical capacity. Thus, an automated cost-efficient decision-making system is implemented to insert into the turnaround process to realize the integrated management of essential ground handling processes.

Figure 8-1 illustrates the role of the developed system. The primary role is scheduling the robust work order by communicating with each work agent who is involved in the aircraft turnaround process. In other words, it sequences the operations for aircraft following which it calls on each work agent to perform their activities. It should share relevant data among the entities. The proposed concept would be capable of handling non-appointed flight schedules identifying the necessary agents and their behavior.

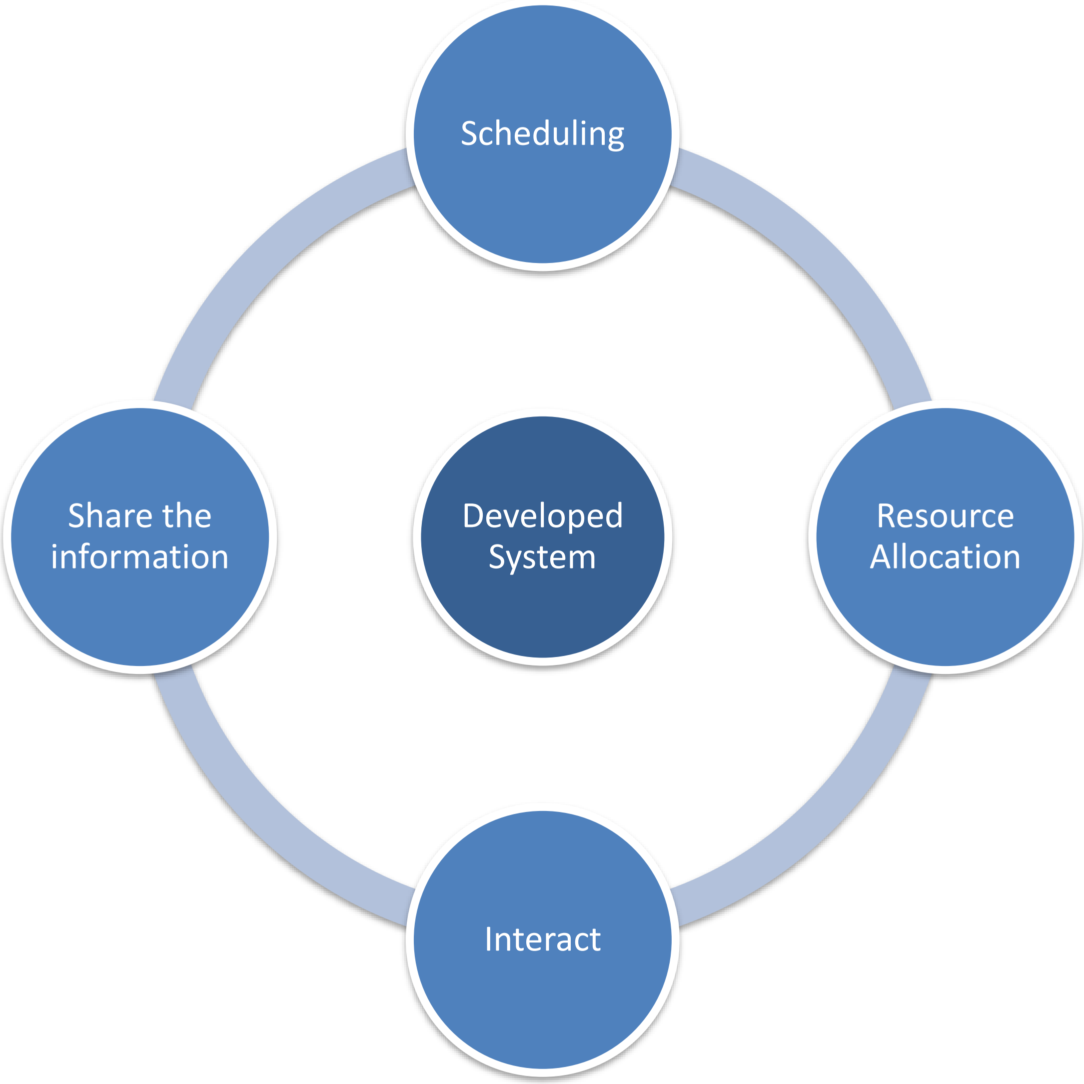


Figure 8-1 Role of Automated Cost-Efficient Decision-Making System

Figure 8-2 illustrates a modeling structure of integrated turnaround system. The system compromises flight schedule analysis, turnaround process analysis and definition of operational scenarios.

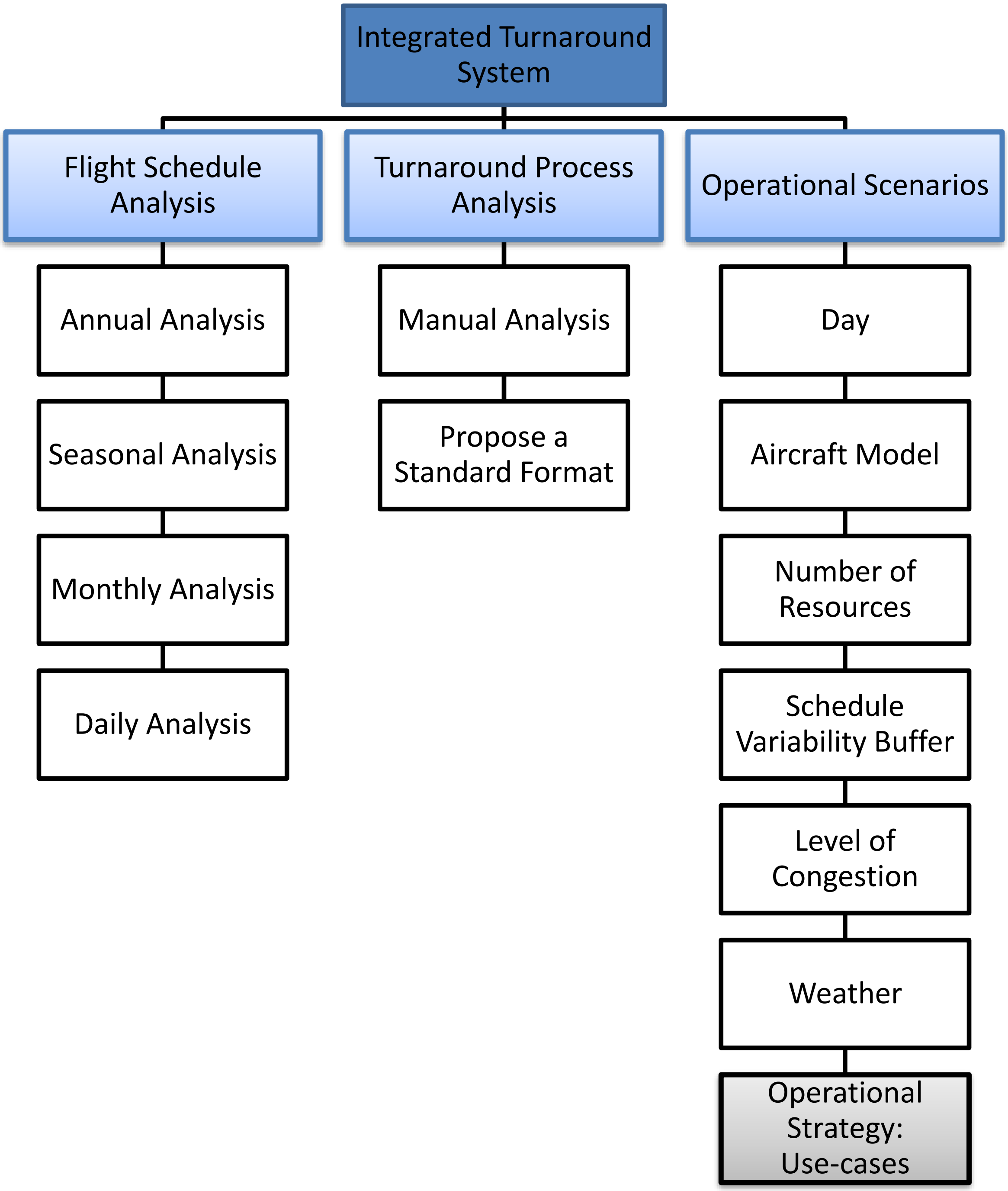


Figure 8-2 Modeling Structure of Integrated Turnaround System

In terms of the use-cases, there are two operational strategies for aircraft queuing. The first strategy is 'SDT (Scheduled Departure Time)': the aircraft that has the earlier scheduled departure time takes a priority for the turnaround activity. The second strategy is ‘FCFS (First-Come-First-Served)’: the aircraft that first arrived takes a priority for the turnaround activity. FCFS reflects how it is done today, and SDT is a suggested concept to make a more stable solution. Hypothesis 3-1 proposed that the scheduled departure time strategy will produce a more stable solution than the first-come-first-served strategy, and it has been substantiated.

Table 8-1 indicates the change in the number of delayed flights and the total delay time in a day from the SDT case to the FCFS case. The results follow the worst number of resources.

$$\Delta = \text{Total delay time } (SDT) - \text{Total delay time (FCFS)}$$

$$\delta = \text{Number of delayed flights } (SDT) - \text{Number of delayed flights (FCFS)}$$

Table 8-1 Comparison of Performance: SDT vs. FCFS

	Δ: **Ideal (hour)**	Δ: **Largest (hour)**	**δ**: **Ideal**	**δ**: **Largest**
Busy-Weekday	-210.46	-343.28	-15	-37
Bust-Weekend	-418.78	-166.28	-14	-17
Normal-Weekday	-160.59	-66.21	-17	-5
Normal-Weekend	-153.42	-70.15	-21	-4

This research assumes that an aircraft model has its own turnaround process and every airline should follow. However, in the real world, each airline has its unique style to handle the aircraft turnaround process such as a different way for queueing the aircraft or a different number of activities. For the application of the centralized approach, it is required that coordinated and aligned consultation among the airlines.

According to table 8-1, SDT queuing should be a more stable solution because it decreases the number of delayed flights and total delay time. Compared with FCFS queuing, SDT queuing demonstrates that it can reduce as few as 60 hours and as many as 400 hours delay in a day up to the amount of schedule variability buffer and level of congestion. This comparison will contribute to overcoming the barrier of actual application because of economic efficiency.

8.2 Contribution

This research touches the area rarely focused on and finds a way to improve it. As mentioned in chapter 1, the turnaround process has not taken center stage in current research in spite of its critical role. The research captures the status and analyzes the available point to improve. Then, using the modeling and simulation techniques, proceed to the demonstration of the suggested new operational concept. In terms of the modeling and simulation techniques, discrete event simulation methodology is used.

A signal-processing environment in the aircraft turnaround process is realized in this work. Signal processing is a conventional technique in computer science. This research works on the integration of signal processing into the aircraft turnaround process. It is a trial to reduce communication problems among the relevant stakeholders.

The simulator produces an entirely parametric environment. It enables decision making with the parametric environment. In terms of the simulator's function, it can capture the delay reason through the turnaround process, i.e., waiting too long for catering resources. In addition, capturing each turnaround activity status is realized including preparation, execution, and post-processing.

The research reflects a realistic environment. The simulator considers the time shift. It allocates more resources in the rush hour is available. In addition, the simulator considers two types of weather: nominal weather and off-nominal weather. Off-nominal weather means severe weather conditions affecting turnaround delay.

8.3 Summary

The research work presented in the current dissertation has explored strategies for improvement in the aircraft turnaround process such that little to no investment from the airlines would be required. This investigation is summarized as the primary objective guiding the research work, given as: "***The development of an approach to provide a stable operational turnaround process with current capacity.***"

In order to portray the traditional turnaround system accurately, the general information of the aircraft turnaround process was reviewed by analyzing the various literature and research works. It highlights the traditional system's weakness:

- No general standard or rule for the aircraft turnaround process
- The collaboration of various stakeholders by pursuing each profit respectively

The proposed approach resulted from the improvement of the weakness was discussed. It aims at the integration over the whole turnaround process within the current physical capacity. By using the methodology 'Discrete Event Simulation,' this dissertation makes a success to produce an automated cost-efficient decision-making system inserted into the turnaround process to realize the integrated management of essential ground handling processes.

APPENDIX A. DESCRIPTION OF CATEGORIES OF AIRCRAFT TURNAROUND PROCESS

According to the International Air Transport Association (IATA) Ground Operations Manual supplement to the Airport Handling Manual, there are seven main categories of activities with sub-categories [59].

A.1 Passenger Handling

Passenger handling encompasses the following functions [59],[11]:

- Ticketing
- Passenger and luggage check-in
- Passenger assistance
- Security screening
- Special services

A.2 Luggage Handling

Luggage handling encompasses the following functions [59]:

- Moving luggage from the check-in area to the departure gate
- Moving luggage from one gate to another during transfers
- Moving luggage from the arrival gate to the luggage claim area

A.3 Cargo/Mail Handling

Cargo handling encompasses the following functions [59]:

- Import cargo
- Transfer cargo
- Export cargo
- Handling of relevant documents and customs procedures

If the airline has a service for mail handling, it mainly deals with incoming and outgoing mail. It also requires the handling of relevant documents. Systematically, there is an effort to implement any security procedure by agreed among the stakeholders to proceed with the cargo/mail handling.

A.4 Aircraft Handling and Loading

Aircraft handling and loading encompass the following functions [59]:

- Operation of aircraft access doors and other access points
- Operation of ground support equipment
- Operation of passenger boarding equipment
- Luggage sorting, transfer luggage and consignments shipped as luggage by courier
- Loading and unloading of luggage, cargo, mail, stores and other items
- Transportation of cargo and luggage
- Coordination of aircraft loading documentation
- Catering
    - Unloading of unused food and drinks from previous flight
    - Loading of fresh food and drinks
- Exterior servicing of an aircraft:

  - The internal and external cleaning of the aircraft
  - The removal of snow and ice on the aircraft

A.5 Aircraft Ground Movement

Aircraft ground movement encompasses the following functions [59]:

- Aircraft taxi-in arrival and taxi-out departure: forward movement of an aircraft to or from the parking position by use of the aircraft engines
- Aircraft pushback: movement of an aircraft from a parking position to a taxi position by use of specialized ground support equipment
- Aircraft towing: movement of an aircraft with or without a load onboard, other than pushback operations, by use of specialized ground support equipment
- Aircraft power back: rearward movement of an aircraft from a parking position to a taxi position by use of the aircraft engines
- Marshaling conducted for the above operations
- Provision of assistance during the above operations

A.6 Load Control

In terms of safety regulation, all actual load boarded on an aircraft should be reported. It includes exact planning, recording, and reporting of all load. To ensure correct weight, documented communication is necessary.

A.7 Airside Supervision and Safety

To ensure all station activities, airside process should be monitored by the direct oversight of supervisory personnel.

APPENDIX B. FLIGHT ARRIVAL DEFINITION

In terms of the simulator development, it is necessary to define flight arrival scenario as an input. Here is an example of the structure of the input deck defining the flight arrival.

Table B-1 Flight Arrival Definition

Date 1	**Date 2**	**Date 3**	**Date 4**
12:02 AM	12:27 AM	12:01 AM	12:06 AM
12:08 AM	12:36 AM	12:24 AM	12:26 AM
12:16 AM	12:37 AM	12:24 AM	12:36 AM
12:30 AM	12:41 AM	12:37 AM	12:45 AM
12:30 AM	1:07 AM	12:42 AM	12:53 AM
12:31 AM	4:41 AM	12:44 AM	4:36 AM
12:35 AM	5:06 AM	12:49 AM	5:05 AM
4:23 AM	5:17 AM	12:51 AM	5:16 AM
5:15 AM	5:22 AM	1:20 AM	5:20 AM
⋮	⋮	⋮	⋮
11:36 PM	11:38 PM	11:54 PM	11:33 PM
11:37 PM	11:41 PM	11:54 PM	11:38 PM
11:39 PM	11:45 PM	11:56 PM	11:45 PM
11:41 PM	11:47 PM	11:59 PM	11:47 PM
11:42 PM	11:52 PM	11:59 PM	11:55 PM

APPENDIX C. ACTIVITY PHASE AND RESOURCE DEFINITION

In terms of the simulator development, it is necessary to define each activity phase and its resources as an input. Here is an example of the structure of the input deck defining the activity.

Table C-1 Activity and Resource Definition

Phase-Substep	Resource Name	Shift1	Shift2	Shift3	Shift4
Deboarding-Prep, Post	deboarding	45	30	25	50
Deboarding-Exec	deboarding_exec	50	50	50	50
catering-Prep, Post	catering	25	20	50	45
catering-Exec	catering_exec	30	30	30	30
cleaning-Prep, Post	cleaning	45	30	25	50
cleaning-Exec	cleaning_exec	50	50	50	50
boarding-Exec	boarding_exec	25	20	50	45
boarding-Prep, Post	boarding	30	30	30	30
unloading-Prep, Post	unloading	45	30	25	50
unloading-Exec	unloading_exec	50	50	50	50
loading-Exec	loading_exec	25	20	50	45
loading-Prep, Post	loading	30	30	30	30
refueling-Prep, Post	refueling	45	30	25	50
refueling-Exec	refueling_exec	50	50	50	50

refueling-Prep, Post	refueling	25	20	50	45
waste-Prep, Post	waste	30	30	30	30
waste-Exec	waste_exec	20	15	30	35
supply-Prep, Post	supply	40	45	60	45
supply-Exec	supply_exec	10	10	10	15

APPENDIX D. AIRCRAFT MODEL DEFINITION

In terms of the simulator development process, it is necessary to define each aircraft model as an input. Here is an example of the structure of the input deck defining the aircraft.

Table D-1 Aircraft Model Definition

Phase	Substep	Required Resource	Required Time	Connectivity
DeBoarding	Wait			
	Prep	deboarding	120	
	Exec	deboarding_exec	450	Prep
	Post	deboarding	120	
Catering	Wait			
	Prep	catering	120	DeBoarding.Exec - 120
	Exec	catering_exec	282	Prep1
	Post	catering	90	Exec1
Cleaning	Wait			
	Prep	cleaning	120	DeBoarding.Exec - 120
	Exec	cleaning_exec	1110	Prep
	Post	cleaning	120	Exec
Boarding	Wait			
	Prep	boarding	180	
	Exec	boarding_exec	762	Catering.Exec

	Post	boarding	210	Exec
UnloadingFwd	Wait			
	Prep	unloading	120	
	Exec	unloading_exec	270	Prep
	Post			
UnloadingAft	Wait			
	Prep	unloading	120	
	Exec	unloading_exec	360	Prep
	Post			
LoadingFwd	Wait		1770	UnloadingFwd.Exec
	Prep			
	Exec	loading_exec	1200	Wait
	Post	loading	90	Exec
LoadingAft	Wait		1590	UnloadingAft.Exec
	Prep			
	Exec	loading_exec	360	Wait
	Post	loading	90	Exec
Refueling	Wait		420	
	Prep	refueling	150	Wait
	Exec	refueling_exec	960	Prep
	Post	refueling	150	Exec

WasteWater	Wait			
	Prep	waste	120	
	Exec	waste_exec	480	Prep
	Post	waste	120	Exec
SupplyingWater	Wait			
	Prep	supply	120	WasteWater.Post
	Exec	supply_exec	300	Prep
	Post	supply	120	Exec

APPENDIX E. TURNAROUND TIME AND SCHEDULE VARIABILITY BUFFER DEFINITION

In terms of the simulator development process, it is necessary to define the turnaround time and schedule variability for each aircraft model. Here is an example of the structure of the input deck defining the aircraft.

Table E-1 Turnaround Time and Schedule Variability Buffer Definition

Model	B737-600	B737-700	···	A350-1000	A380
Turnaround Time (sec)	1980	2400	···	4200	5400
Buffer Time (sec)	0	0	···	0	0

APPENDIX F. OUTPUT DEFINITION

In terms of the performance of the simulator, it produces one output file storing the entire process of simulation. Here is an example of the structure of the output deck.

Arrival column shows the index of arrival time as defined in the input file ‘flight arrival’. The scheduled times are given in parentheses, and the real times are given without parentheses. The number means the time from the flight arrival.

Table F-1 Output Definition

Arrival	Aircraft	Refueling.Exec (sec)	Refueling.Post (sec)	Refueling.Prep (sec)	…	Time.Departure (sec)	Catering1.Exec (sec)	Catering1.Post (sec)
0	B747-400	1680.0 (1680.0)	120.0 (120.0)	120.0 (120.0)	…	3660 (3660)	1800.0 (1800.0)	120.0 (120.0)
1	B777-300ER	2520.0 (2520.0)	510.0 (480.0)	480.0 (480.0)	…	3510 (3480)	450.0 (450.0)	120.0 (120.0)
2	A350-1000	2160.0 (2160.0)	510.0 (480.0)	480.0 (480.0)	…	4290 (4200)	1080.0 (1056.0)	180.0 (180.0)
3	B747-400	1680.0 (1680.0)	120.0 (120.0)	120.0 (120.0)	…	3690 (3660)	1800.0 (1800.0)	120.0 (120.0)
4	B787-9	2130.0 (2100.0)	480.0 (480.0)	480.0 (480.0)	…	3090 (3060)	630.0 (600.0)	60.0 (60.0)
5	B787-9	2130.0 (2100.0)	480.0 (480.0)	480.0 (480.0)	…	3090 (3060)	630.0 (600.0)	60.0 (60.0)
6	B787-10	2100.0 (2100.0)	480.0 (480.0)	480.0 (480.0)	…	4080 (3360)	780.0 (780.0)	60.0 (60.0)
7	B737-600	570.0 (540.0)	120.0 (120.0)	120.0 (120.0)	…	1770 (1980)	300.0 (300.0)	120.0 (120.0)
8	B737-600	540.0 (540.0)	120.0 (120.0)	120.0 (120.0)	…	1770 (1980)	300.0 (300.0)	150.0 (120.0)
9	A350-1000	2160.0 (2160.0)	480.0 (480.0)	480.0 (480.0)	…	4290 (4200)	1080.0 (1056.0)	180.0 (180.0)
10	B737-600	540.0 (540.0)	120.0 (120.0)	120.0 (120.0)	…	1740 (1980)	300.0 (300.0)	120.0 (120.0)
11	A320-200	960.0 (960.0)	150.0 (150.0)	150.0 (150.0)	…	3450 (2652)	300.0 (282.0)	90.0 (90.0)

12	B737-600	540.0 (540.0)	120.0 (120.0)	120.0 (120.0)	...	1770 (1980)	300.0 (300.0)	120.0 (120.0)
13	B737-600	540.0 (540.0)	120.0 (120.0)	120.0 (120.0)	...	1740 (1980)	300.0 (300.0)	120.0 (120.0)

APPENDIX G. ADDITIONAL EXPERIMENTAL RESULTS

In terms of the performance evaluation, all the additional results are illustrated here.

G.1 FCFS- Busy, Weekday, and Nominal Weather

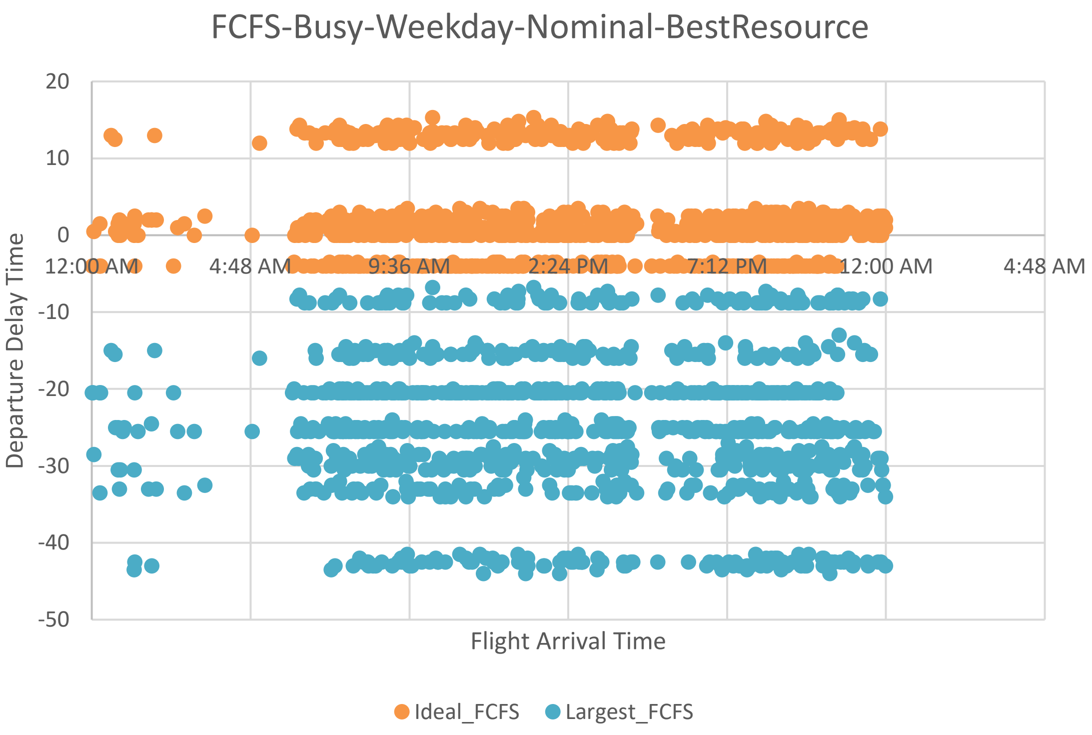


Figure G-1 Departure Delay Distribution – FCFS, Busy, Weekday, Nominal Weather and Best Resources

Figure G-1 shows the expanded version of the departure delay distribution: the busy season's weekday schedule with the best resources under nominal weather scenario. The maximum value of the y-axis is 20 minutes. The ideal cases are mainly located in upwards area of the x-axis, and the largest cases are mainly located in the downwards area of the x-axis.

G.2 FCFS- Busy, Weekend, and Nominal Weather

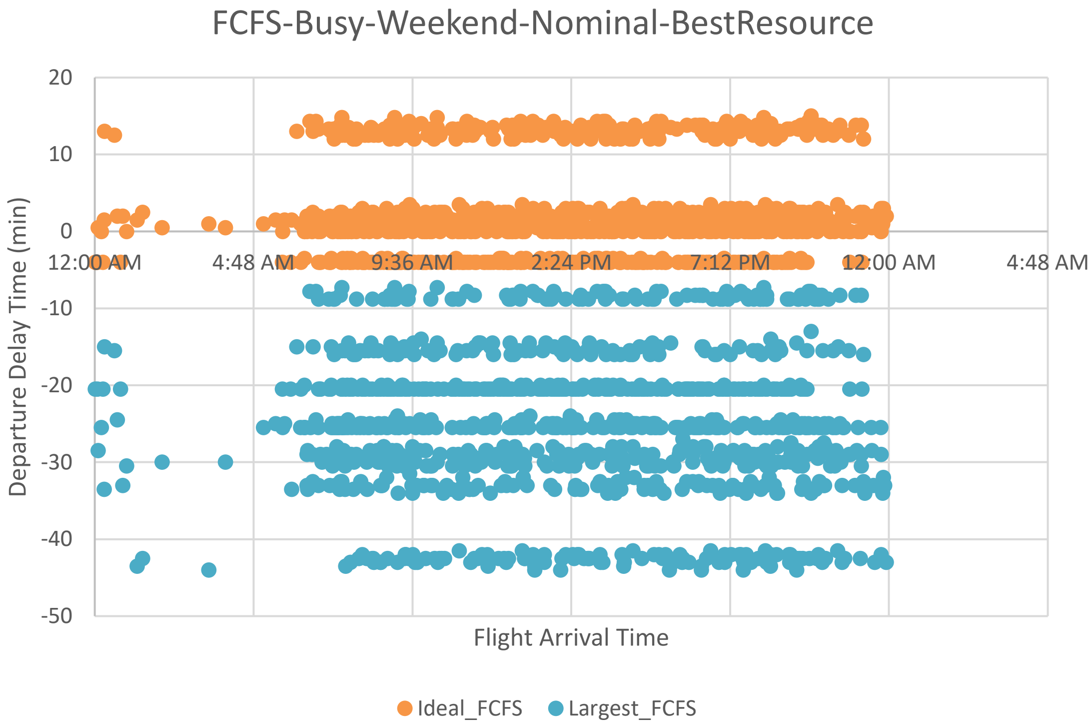


Figure G-2 Departure Delay Distribution – FCFS, Busy, Weekend, Nominal Weather and Best Resources

Figure G-2 shows the expanded version of the departure delay distribution: the busy season’s weekend schedule with the best resources under nominal weather scenario. The maximum value of the y-axis is 20 minutes. The ideal cases are mainly located in upwards area of the x-axis, and the largest cases are mainly located in the downwards area of the x-axis.

G.3 FCFS- Normal, Weekday, and Nominal Weather

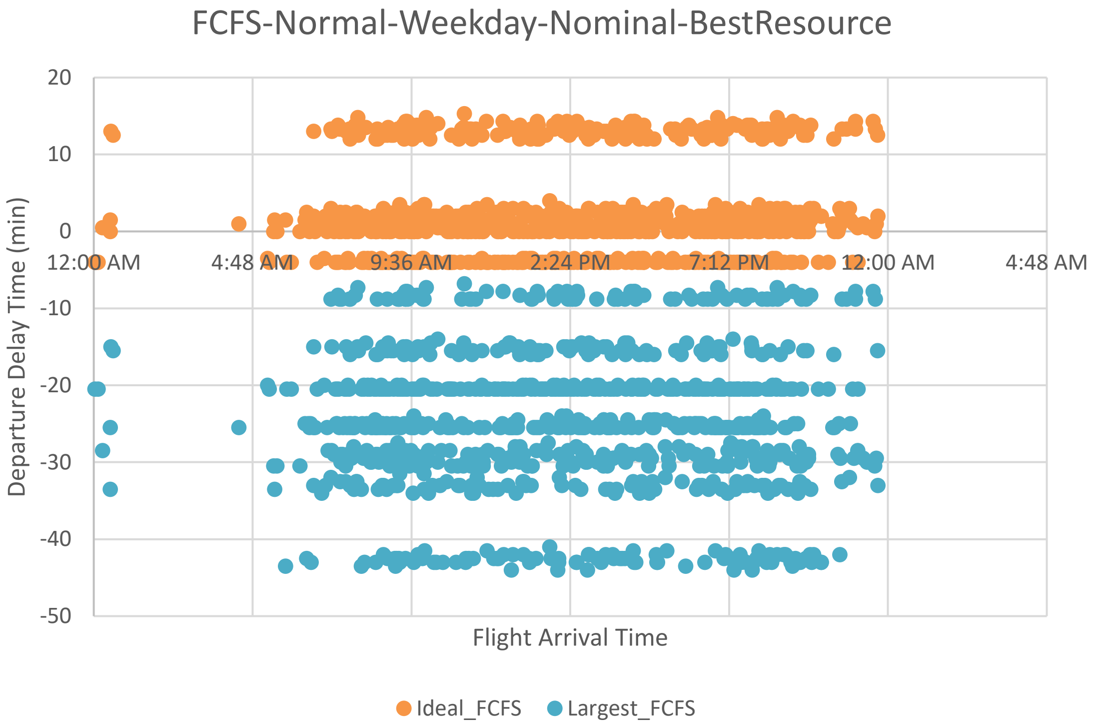


Figure G-3 Departure Delay Distribution – FCFS, Normal, Weekday, Nominal Weather and Best Resources

Figure G-3 shows the expanded version of the departure delay distribution: the normal season's weekday schedule with the best resources under nominal weather scenario. The maximum value of the y-axis is 20 minutes. The ideal cases are mainly located in upwards area of the x-axis, and the largest cases are mainly located in the downwards area of the x-axis.

G.4 FCFS- Normal, Weekend, and Nominal Weather

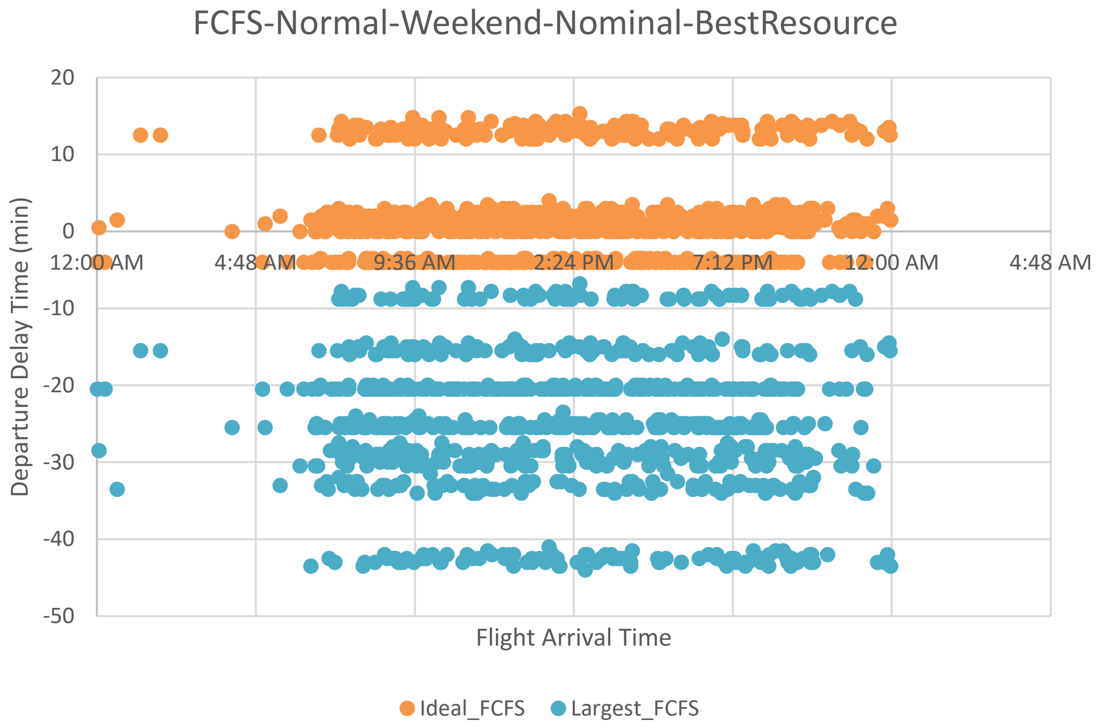


Figure G-4 Departure Delay Distribution – FCFS, Normal, Weekend, Nominal Weather and Best Resources

Figure G-4 shows the expanded version of the departure delay distribution: the normal season's weekend schedule with the best resources under nominal weather scenario. The maximum value of the y-axis is 20 minutes. The ideal cases are mainly located in upwards area of the x-axis, and the largest cases are mainly located in the downwards area of the x-axis.

G.5 SDT- Busy, Weekday, and Nominal Weather

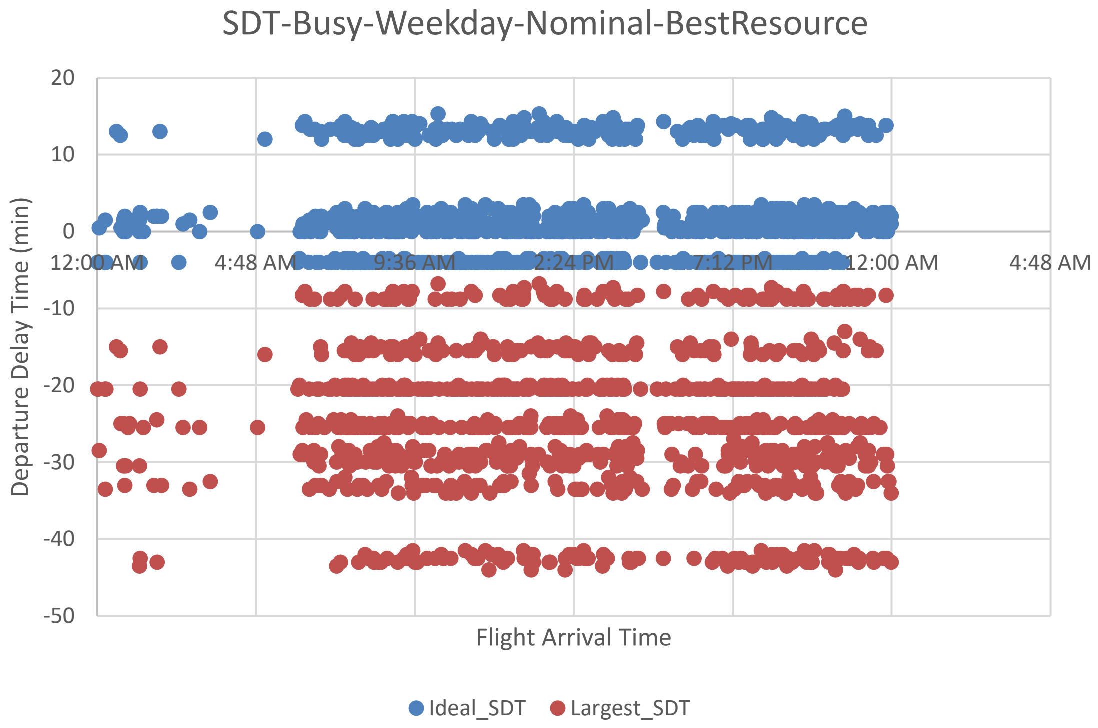


Figure G-5 Departure Delay Distribution – SDT, Busy, Weekday, Nominal Weather and Best Resources

Figure G-5 shows the departure delay time of each arrival from the busy season’s weekday schedule with the best case of a number of resources. The weather is assumed as nominal. For the resources, it has an unlimited number of resources for every activity: deboarding, boarding, catering, cleaning, loading, unloading, refueling, supplying water, and waste water activity.

A total of three flights from 1103 arrived flights are evaluated as a delayed flight for the ideal case of the schedule variability buffer. Furthermore, a total of 219 flights had an early departure than their scheduled departure time.

For the largest case of the schedule variability buffer, there is no flight, which identified as a delayed flight. In that case, all 1103 flights had an early departure with respect to their scheduled departure time, which means having a negative delay time value.

G.6 SDT- Busy, Weekend, and Nominal Weather

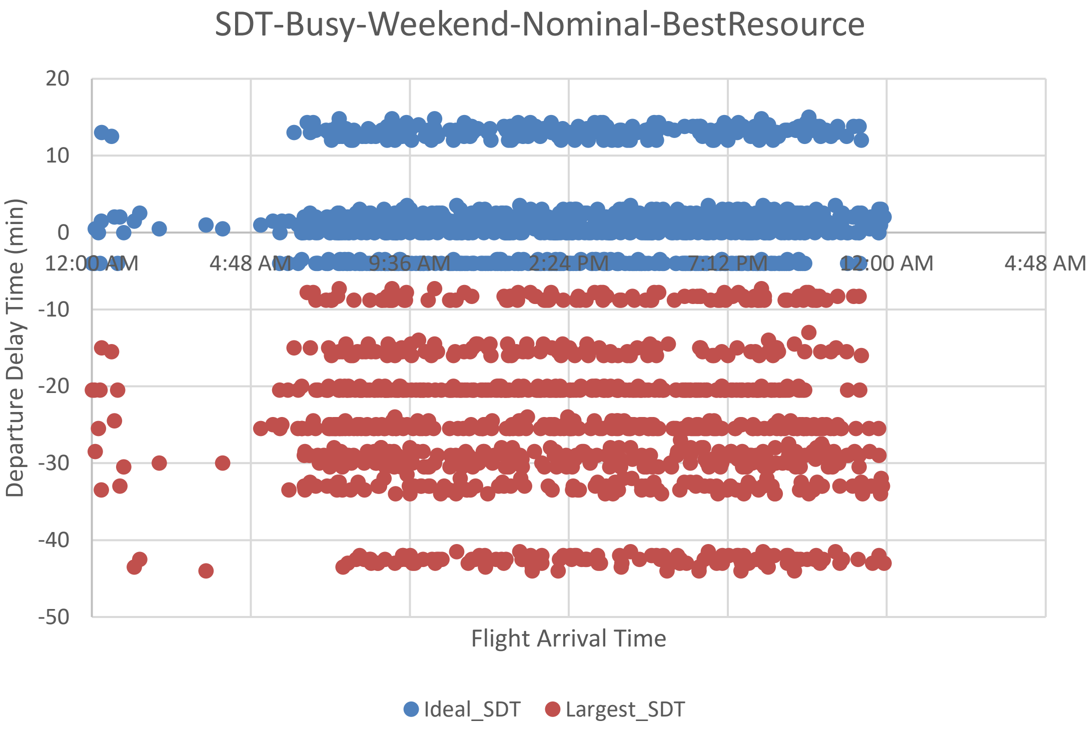


Figure G-6 Departure Delay Distribution – SDT, Busy, Weekend, Nominal Weather and Best Resources

Figure G-6 shows the departure delay time of each arrival from the busy season's weekend schedule with the best case of a number of resources. Thus, it has an unlimited number of resources for every activity: deboarding, boarding, catering, cleaning, loading, unloading, refueling, supplying water, and waste water activity.

Only one flight from the arrived flights is evaluated as a delayed flight for the ideal case of the schedule variability buffer. Furthermore, a total of 221 flights had early departure than their scheduled departure time.

For the largest case of the schedule variability buffer, there is no flight, which identified as a delayed flight. In that case, a total of 1119 flights had early departure with respect to their scheduled departure time, which means having a negative delay time value. Likewise, the best case results show the strip-shaped distribution.

G.7 SDT- Normal, Weekday, and Nominal Weather

Figure G-7 shows the departure delay time of each arrival from the normal season's weekday schedule with the best case of a number of resources. It results from the nominal weather condition. For the resources, it has an unlimited number of resources for every activity: deboarding, boarding, catering, cleaning, loading, unloading, refueling, supplying water, and waste water activity.

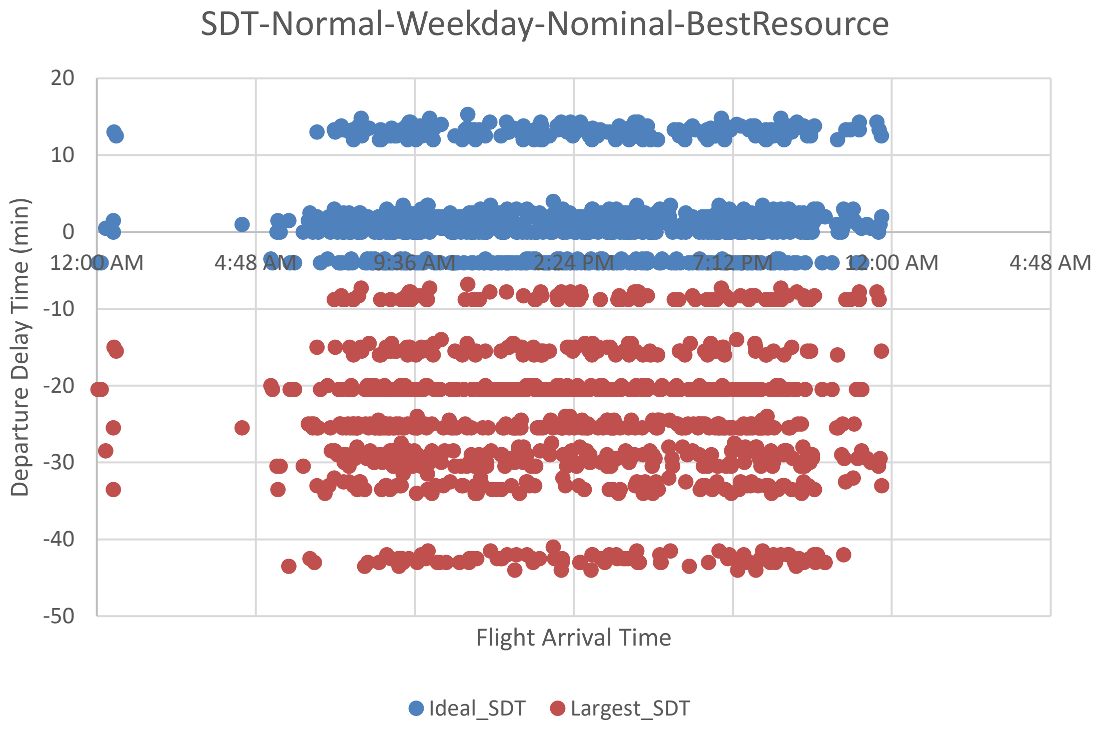


Figure G-7 Departure Delay Distribution – SDT, Normal, Weekday, Nominal Weather and Best Resources

Likewise, the best case has a strip-shaped distribution regardless of the case of schedule variability buffer. Therefore, for the best case for the resources, the schedule variability buffer has a lower impact on a flight delay. The following explains the numerical value of delayed flight.

There is only one delayed flight for the ideal case of the schedule variability buffer. Furthermore, a total of 195 flights finished their take-off preparation and departed before their scheduled departure time. For the largest case of the schedule variability buffer, no flight is under the delayed flights. In that case, all 951 flights had early departure than their scheduled departure time, which means having a negative delay time value.

G.8 SDT- Normal, Weekend, and Nominal Weather

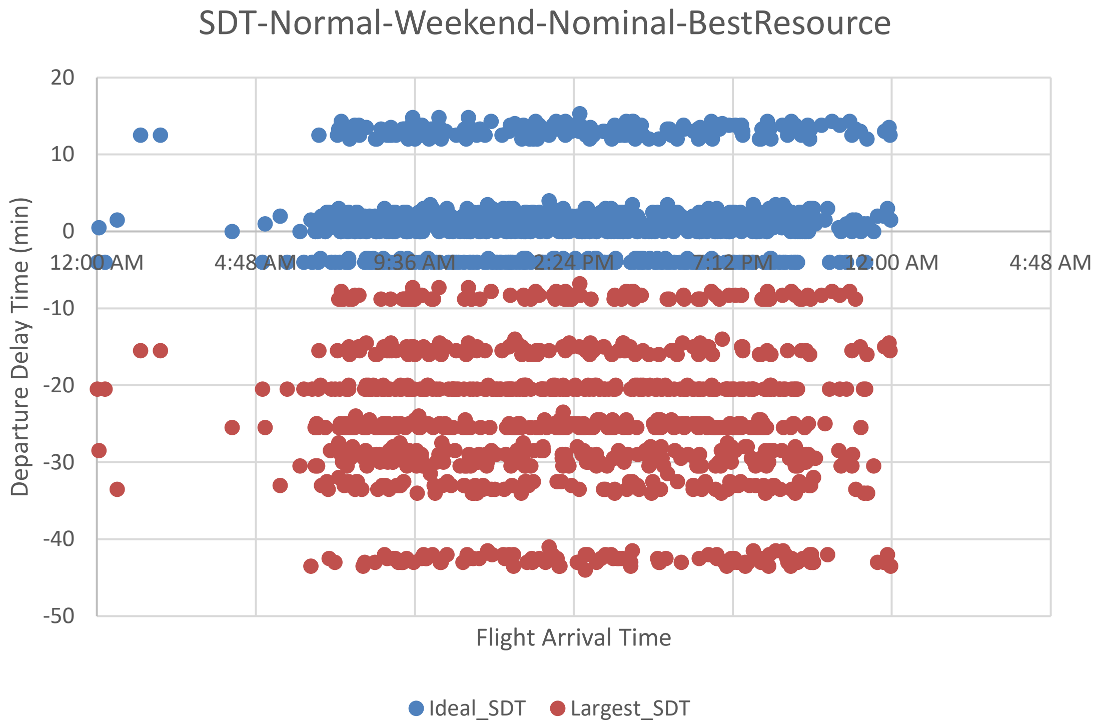


Figure G-8 Departure Delay Distribution – SDT, Normal, Weekend, Nominal Weather and Best Resources

Figure G-8 shows the departure delay time of each arrival from the normal season’s weekend schedule with the best case of a number of resources. For the resources, it follows the best case’s scenario. Thus, it has an unlimited number of resources for all activity: deboarding, boarding, catering, cleaning, loading, unloading, refueling, supplying water, and waste water — the figure results from the nominal weather condition.

Only one flight from 967 arrived flights is evaluated as a delayed flight for the ideal case of the schedule variability buffer. Furthermore, a total of 198 flights had early departure than their scheduled departure time. For the largest case of the schedule variability buffer, there is no flight, which is labeled as a delayed flight. Thus, all 967 flights finished all the ground activities earlier than their scheduled departure time and made an early departure. The figure shows that this best case has a strip-shaped distribution.

G.9 SDT- Busy, Weekday, and Off-nominal Weather

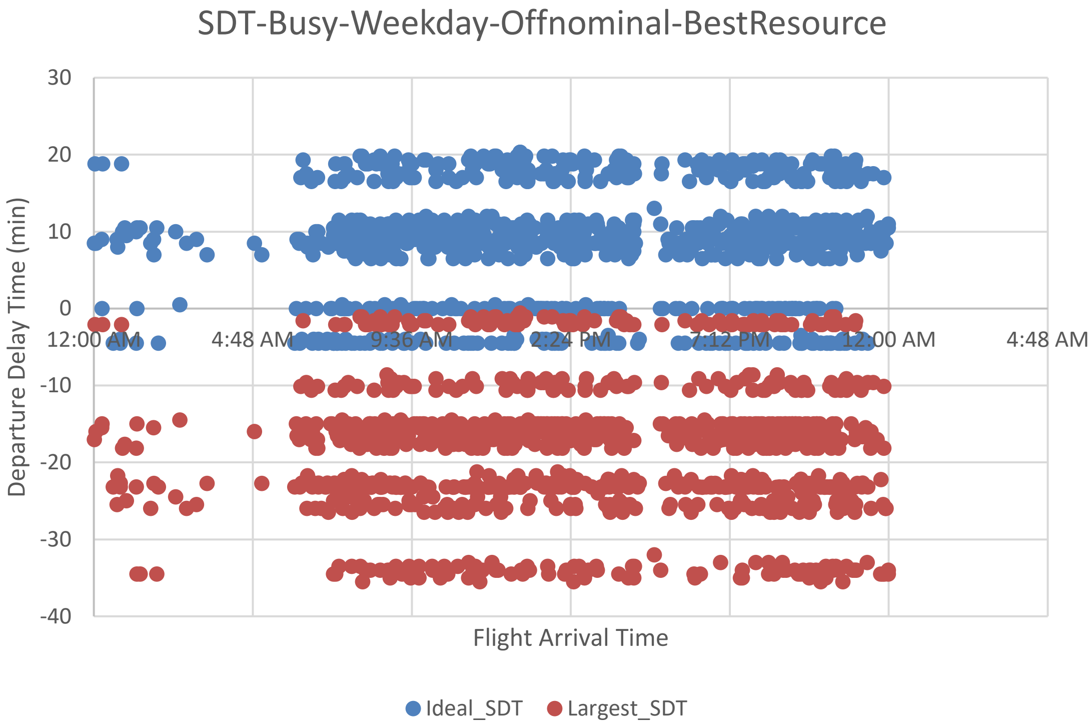


Figure G-9 Departure Delay Distribution – SDT, Busy, Weekday, Off-Nominal Weather, and Best Resources

Figure G-9 shows the departure delay time of each arrival by SDT strategy under the off-nominal weather condition, but it applies the best case for the number of resources. Thus, it has an unlimited number of resources for every activity: deboarding, boarding, catering, cleaning, loading, unloading, refueling, supplying water, and waste water activity. The flight arrival scenario is from the busy season’s weekday.

For the largest case of the schedule variability buffer, there is no flight, which identified as late. In that case, all flights had early departure than their scheduled departure time, which means having a negative delay time value. The largest case of the resources has a growing trend of the departure delay time, and the longest delay time is recorded around ten hours.

G.10 SDT- Busy, Weekend, and Off-nominal Weather

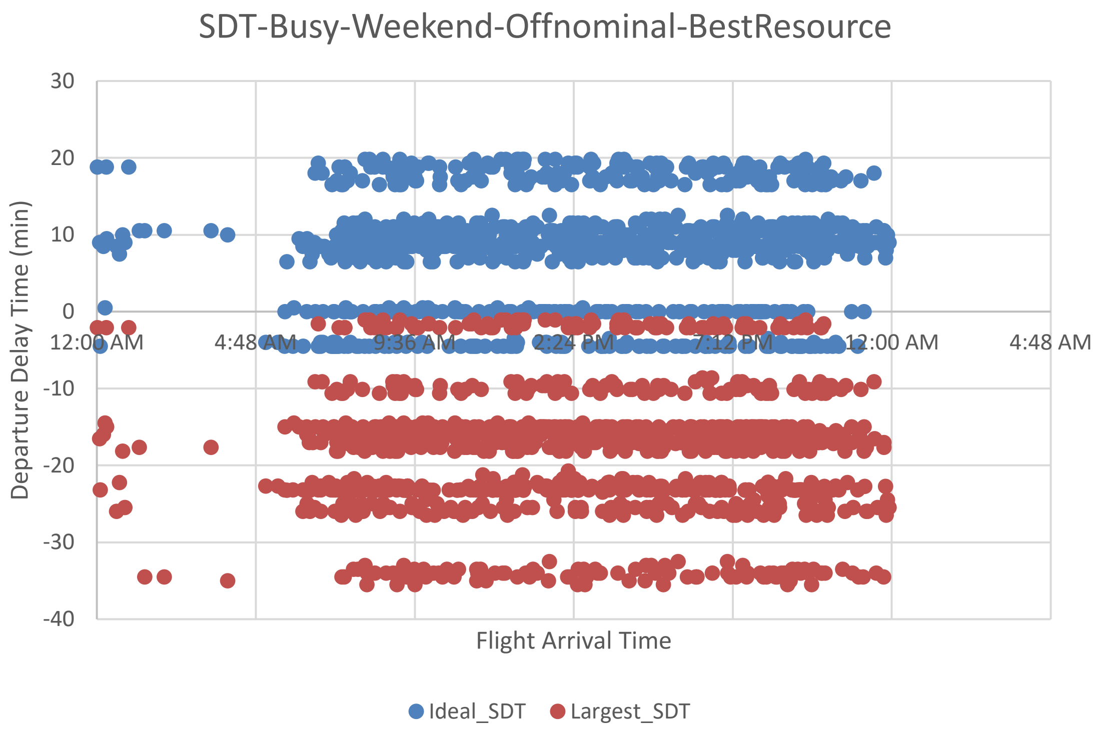


Figure G-10 Departure Delay Distribution – SDT, Busy, Weekend, Off-Nominal Weather, and Best Resources

Figure G-10 shows the departure delay time of each arrival with the busy season's weekend schedule. It operates by SDT strategy under the off-nominal weather condition. For the resources, it works with the best case of a number of resources. Thus, it has an unlimited number of resources for every activity: deboarding, boarding, catering, cleaning, loading, unloading, refueling, supplying water, and waste water activity.

G.11 SDT- Normal, Weekday, and Off-nominal Weather

Figure G-11 shows the departure delay time of each arrival from the normal season’s weekday schedule. It results from the nominal weather condition and follows the best case of a number of resources. Thus, it has an unlimited number of resources for every activity: deboarding, boarding, catering, cleaning, loading, unloading, refueling, supplying water, and waste water activity.

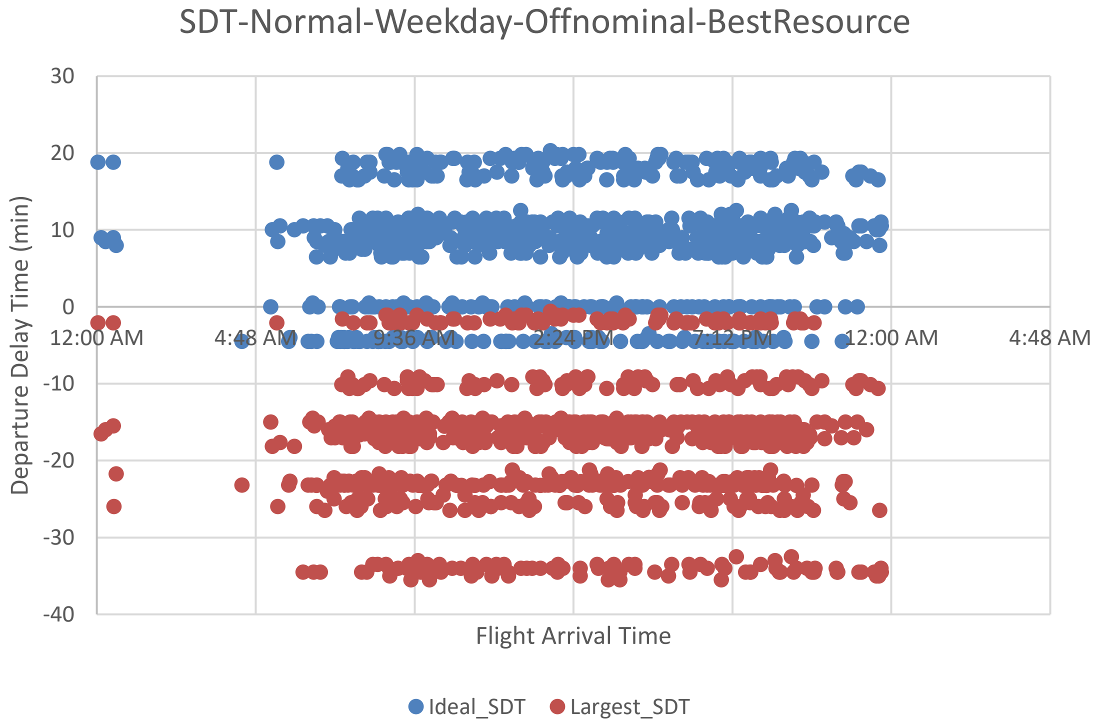


Figure G-11 Departure Delay Distribution – SDT, Normal, Weekday, Off-Nominal Weather, and Best Resources

Regardless of the case of schedule variability buffer, the best case has strip-shaped distribution. However, the ideal case is located in an upward area than the largest case. To analyze the impact of the schedule variability buffer, the number of delayed flights is tracked.

There are a total of 187 delayed flights for the ideal case of the schedule variability buffer. Furthermore, a total of 98 flights finished their take-off preparation and departed before their scheduled departure time.

For the largest case of the schedule variability buffer, there is no delayed flight. In that case, a total of 951 flights had early departure than their scheduled departure time.

G.12 SDT- Normal, Weekend, and Off-nominal Weather

Figure G-12 shows the departure delay time of each arrival when working with the normal season’s weekend schedule. It occurred under the off-nominal weather condition.

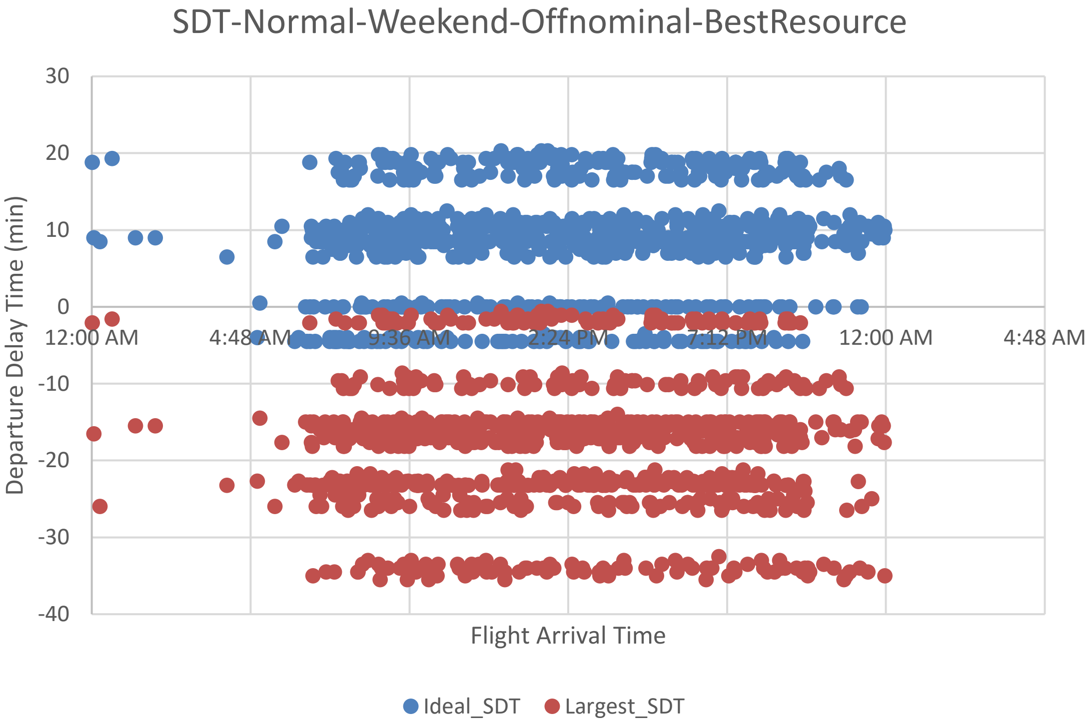


Figure G-12 Departure Delay Distribution – SDT, Normal, Weekend, Off-Nominal Weather, and Best Resources

For the resources, it follows the best case's scenario. Thus, it has an unlimited number of resources for all activity: deboarding, boarding, catering, cleaning, loading, unloading, refueling, supplying water, and waste water.

For the ideal case of the schedule variability buffer, a total of 187 flight from 967 arrived flights are labeled as a delayed flight. The longest delay time is 20.3 minutes. Furthermore, a total of 98 flights made their early departure than the scheduled departure time.

For the largest case of the schedule variability buffer, there is no flight, which classified as a delayed flight. Thus, a total of 967 flights finished all ground activities, which are necessary to take-off, earlier than their scheduled departure time.

REFERENCES

[1] Dillingham, G. L. “Delays and enhance capacity are ongoing but challenges remain,” Technical report, United States Government Accountability Office, (2005)

[2] Hanbong lee, “Tradeoff evaluation of scheduling algorithms for terminal-area air traffic control,” Master Thesis (S.M.), Massachusetts Institute of Technology (2008)

[3] Kari Andersson, Francis Carr, Eric Feron and William D. Hall, “Analysis and Modeling of Ground Operations at Hub Airports,” Third USA/Europe Air Traffic Management R&D Seminar, (2000)

[4] Yoshinori Suzuki, “The Relationship between on time Performance and Airline Market Share,” Transportation Research Part E: Logistics and Transportation Review, 36 (2), 139-154 (2000)

[5] Mazhar Arikan, “The Impact of Airline Flight Schedules on Flight Delays: an Analysis of Block-Time, Delay Propagation, and Schedule Optimization Using Stochastic Models,” Ph. D dissertation, Purdue University (2011)

[6] Unites States Department of Transportation, Bureau of Transportation Statistics, Airline On-Time Statistics and Delay Causes (2003)

[7] Unites States Department of Transportation, Bureau of Transportation Statistics, National Departure Delays (2016)

[8] Wong, “A survival model for flight delay propagation”, Journal of Air Transport Management (2012) 5-11

[9] Fricke, “Delay Impacts onto Turnaround Performance,” USA/Europe Air Traffic Management Research and Development Seminar (2009)

[10] Eurocontrol, Airport CDM Implementation (2012)

[11] Koluskisa, “Evaluating Aircraft Turnaround Process in the Framework of Airport Design and Airline Behaviour,” Doctor of Philosophy of Faculdade de Engenharia da Universidade do Porto (2012)

[12] Fuhr, "(De)regulation of the European Ramp Handling Market-Lessons to Be Learned from an Institutional Perspective," Working Paper, Workgroup for Infrastructure Policy, Technische Universitat Berlin (2006)

[13] IATA, Airline and Aircraft Operations (2015)

[14] Boeing, 747-400 Airplane Characteristics for Airport Planning

[15] Savine Wilke, Arnav Majumdar, Washington Y. Ochieng, "Airport surface operations: A holistic framework for operations modeling and risk management," Safety Science 63 (2014), 18-33

[16] Speed and safety in refueling, Airport Technology Market & Customer Insight (2011)

[17] Dennis Burchell, Fuels Maintenance Group International, an Interviewed article in Magazine Vanguard (2011)

[18] Antonín Kazda, Martin Hromádka, "How to improve airport operation", Centre of Excellence for Air Transport, ITMS 26220120065. (2011)

[19] Stewart Robinson, Gilbert Arbez, and Louis G. Birta, "Conceptual Modeling: Definition, Purpose and Benefits," Proceedings of the Winter Simulation Conference (2015)

[20] Stewart Robinson, "Conceptual Modeling for Simulation Part I: Definition and Requirements," Journal of the Operational Research Society 59 (3): 278-290, (2008)

[21] Barnes, Arthur G., and Thomas J. Yager. "Enhancement of aircraft ground handling simulation capability," Advisory Group for Aerospace Research & Development, (1998)

[22] Gok, Y.S., "Scheduling of aircraft turnaround operations using mathematical modelling: Turkish low-cost airline as a case study," Master of Science Thesis, Coventry University. (2014)

[23] Atkins, Stephen, et al. "Analysis and Modeling of Ground Operations at Hub Airports," (2000)

[24] W.H. Ip, Vincent Cho+, Nick Chung and George Ho, "A Multi Agent-Based Model for Airport Service Planning," International Journal of Engineering Business Management, Vol. 2, No. 2 (2010), 93-100

[25] Averill Law, "Simulation Modeling and Analysis"

[26] Sara Sanz De Vicente, "Ground Handling Simulation with CAST," Master Thesis (2010)

[27] Norin, A. "Airport Logistics- Modeling and Optimizing the Turn-Around Process," Linköping University (2008)

[28] Kunze, T. M., Schultz, and H. Fricke "Aircraft Turnaround management in a highly automated 4 D flight operations environment", International Conference on Application and Theory of Automation in Command and Control Systems, Barcelona, (2011)

[29] Mao, X., Roos, N., and Salden, A. (2009) "Stable multi-project scheduling of airport ground handling services with heterogeneous agents." in AAMAS 2009, 537– 544

[30] Trabelsi S. F., Cosenza A. N., Cruz L. G. Z., Mora-Camino, F. "An operational approach for ground handling management at airports with imperfect information in Iglesias, C. H., Pérez Ríos, J. M. (ed.) Proceedings of the ICIEOM 2013, 19th International Conference on Industrial Engineering and Operations Management. (2013)

[31] Vidosavljević, A., and Toŝić, V. "Modeling of Turnaround Process Using Petri Nets." ATRS World Conference (2010)

[32] Cheng-lung Wu, Airline Operations and Delay Management: Insights from Airline Economics, Networks and Strategic Schedule Planning, Ashgate Publishing, Ltd., (2016)

[33] Cheng-lung Wu and Robert E. Caves 'Modelling and Optimization of Aircraft Turnaround Time at an Airport', Transportation Planning and Technology, Col.27, No. 1. Pp 47-66, (2004)

[34] Theo Horstmeier, Floris de Haan, "Influence of ground handling on turn round time of new large aircraft," Aircraft Engineering and Aerospace Technology, Vol. 73 Issue: 3, pp.266-271 (2001)

[35] IATA Ground Operations Manual (IGOM) Supplement to Airport Handling Manual (2013)

[36] Salma Fitouri-Trabelsi, Carlos Cosenze, Walid Moudani, and Felix Mora-Camino, “Managing Uncertainty at Airports Ground Handling,” Airports in Urban Networks (2014)

[37] Salma Fitouri-Trabelsi, Carlos Cosenze, and Felix Mora-Camino. “Ground Handling Management at Airports with Fuzzy Information,” 6th IFAC Conference on Management and Control of Production and Logistics, International Federation of Automatic Control, 6 (1), pp 373-378 (2013)

[38] Salma Fitouri-Trabelsi, Carlos Cosenze, Zelaya-Cruz Luis Gustavo and Felix Mora-Camino, “An Operational Approach for Ground Handling Management at Airports with Imperfect Information,” 19th International Conference on Industrial Engineering and Operations Management, (2013)

[39] Sanya Adeleye, Christopher Chung “A Simulation-Based Approach for Contingency Planning for Aircraft Turnaround Operation System Activities in Airline Hubs,” Journal of Air Transportation, Volume 11, No. 2; 140-155; (2006)

[40] Cheng, Yu “Network-based simulation of aircraft at gates in airport terminals,” Journal of Transportation Engineering, 124(2). 188-196. (1998)

[41] Handbook of Networked and Embedded Control Systems, Birkhäuser Boston, pp. 71-89 (2005)

[42] Matt R. Jardin, David Manegold, and Anuja Apte, “Discrete-Event Simulation of Air Traffic Flow,” American Institute of AA Guidance and Navigation (2000)

[43] H. Conrad Cunningham, "Chapter 3 of the book Practical Process Simulation: Using Object-Oriented Techniques” (2000)

Rauch R., Kljajić M., “Discrete Event Passenger Flow Simulation Model for an Airport Terminal Capacity Analysis” (2006)

[45] Guizzi G., Murino T. and Romano E, “A Discrete Event Simulation to model Passenger Flow in the Airport Terminal” (2009)

[46] Wu and Caves, Modeling and Simulation of Aircraft Turnaround Operations at Airports, (2004)

[47] Liebeck, R.H., et. Al., “Advanced Subsonic Airplane design and Economic Studies,” NASA CR-195443, (1995)

[48] Ross, T. E., “Designing for Minimum Cost: A Method to Assess Commercial Aircraft Technologies,” Purdue University (1998)

[49] Oliveira “Development of Operating Cost Models for the Preliminary Design Optimization of an Aircraft,” Master of Science Degree in Aerospace Engineering (2015)

[50] Tatsuya Kotegawa and Charlene Cayabyab, Noam Almog and Olga Agafonova, “Estimation of Airline Benefits from Avionics Upgrade under Preferential Merge Re-Sequence Scheduling,” AIAA (2013)

[51] Rashid Ali & Omran Al-Shamma, “A Comparative Study of Cost Estimation Models used for Preliminary Aircraft Design,” Global Journal of Researches in Engineering: B Automotive Engineering Volume 14 Issue 4 Version 1.0 (2014)

[52] Gómez, Francisco & Scholz, Dieter. (2009). IMPROVEMENTS TO GROUND HANDLING OPERATIONS AND THEIR BENEFITS TO DIRECT OPERATING COSTS. Deutscher Luft- und Raumfahrtkongress 2009, At Aachen, Germany

[53] M. Abd Allah Makhloof, M. Elsayed Waheed & Usama A. El-Raouf Badawi “Real-time aircraft turnaround operations manager,” Production Planning & Control, 25:1,2-25, DOI: 10.1080/09537287.2012.655800 (2014)

[54] Aguanno K (2002) Critical Path: An Extended Definition, (available online http://www.agilepm.com/downloads/CPMdefinition.pdf [accessed on 19/11/2012])

[55] Federal Aviation Administration, Certification of aircraft, Categories

[56] AIRBUS S.A.S: A320 Airplane Characteristics for Airport Planning. Airbus S.A.S Technical Data Support and Services, (1995)

[57] Bureau of Transportation Statistics, Atlanta Georgia, Summary data for U.S. Flights only.

[58] Miguel Mujica Mota, Idalia Flores De La Mota, “Applied Simulation and Optimization 2: New Applications in Logistics, Industrial and Aeronautical Practice”, Springer International Publishing AG (2017)

[59] IATA Airport Handling Manual (2015)

[60] Ashford N., Stanton M., and Moore C. ‘Airport Operations’, New York: McGraw-Hill (1997)

[61] Lucy Budd, Stephen Ison ‘Air Transport Management: An International Perspective’, Routledge Taylor and Francis Group, (2017)

[62] Eric R. Mueller and Gano B. Chatterji, “Analysis of Aircraft Arrival and Departure Delay Characteristics,” AIAA's Aircraft Technology, Integration, and Operations (ATIO) (2002)

[63] Osman Balci, “Principles and Techniques of Simulation Validation, Verification, and Testing,” Proceedings of the Winter Simulation Conference Ed. C. Alexopoulos, K. Kang, W. R. Lilegdon, and D. Goldsman (1995)

[64] Wallace D. R. and R. U. Fujii. Software verification and validation: an overview, IEEE Software, Vol. 6, No. 3, pp. 10-17, (1989)

[65] Boehm B.W., Software engineering economics, IEEE Trans. on Software Eng., Vol. 10, no. 1, pp. 4 - 21. (1984)

[66] David Kung, Hong Zhu, ‘Software Verification and Validation’, Encyclopedia of Computer Science and Engineering, Benjamin Wah (Ed.), John Wiley & Sons, Inc. (2008)

[67] “Want To Be On Time? The Airlines And Airports Ranked Highest for Punctuality”, Washington Post, Retrieved from https://www.washingtonpost.com/lifestyle/travel/want-to-be-on-time-the-airlines-and-airports-ranked-highest-for-punctuality/2016/01/08/a96d44fc-b637-11e5-a76a-0

[68] Al-Bahadili, Hussein. (2009). On the Use of Discrete-Event Simulation in Computer Networks Analysis and Design. 10.4018/978-1-60566-774-4.ch019.

[69] Craig Hoyle, "WORLD AIRLINER DIRECTORY," Flight Global. Mainliners: new arrivals. (2017)

[70] 737 Airplane Characteristics for Airport Planning, Boeing Commercial Airplanes

[71] 777-200LR / -300ER / -Freighter Airplane Characteristics for Airport Planning, Boeing Commercial Airplanes

[72] 787 Airplane Characteristics for Airport Planning, Boeing Commercial Airplanes

[73] 747-400 Airplane Characteristics for Airport Planning, Boeing Commercial Airplanes

[74] A320 Aircraft Characteristics Airport and Maintenance Planning, Airbus S.A.S.

[75] A330 Aircraft Characteristics Airport and Maintenance Planning, Airbus S.A.S.

[76] A350 Aircraft Characteristics Airport and Maintenance Planning, Airbus S.A.S.

[77] A380 Aircraft Characteristics Airport and Maintenance Planning, Airbus S.A.S.

[78] Introduction to Transportation Analysis, Modeling and Simulation, Springer

[79] Kuster J., Jannach D. (2006) Handling Airport Ground Processes Based on Resource-Constrained Project Scheduling. In: Ali M., Dapoigny R. (eds) Advances in Applied Artificial Intelligence. IEA/AIE 2006. Lecture Notes in Computer Science, vol 4031. Springer, Berlin, Heidelberg

[80] Py Qt 5.11.1 Reference Guide, The Qt Company, http://pyqt.sourceforge.net/Docs/PyQt5/

[81] Qt Documentation Archives: Signals and Slots, The Qt Company, https://doc.qt.io/archives/qt-4.8/signalsandslots.html

[82] Yuan, D., Flight Delay-Cost Simulation Analysis and Airline Schedule Optimization, Doctor of Philosophy, Aerospace Mechanical and Manufacturing Engineering, RMIT University (2007)

[83] Airlines For America | U.S. Passenger Carrier Delay Costs, http://airlines.org/dataset/per-minute-cost-of-delays-to-u-s-airlines/

[84] Allen M, Spencer A, Gibson A, et al. Right cot, right place, right time: improving the design and organisation of neonatal care networks – a computer simulation study. Southampton (UK): NIHR Journals Library; 2015 May. (Health Services and Delivery Research, No. 3.20.) Chapter 5, What is discrete event simulation, and why use it?

[85] Garrido, J.M., Schlesinger, R., and Hoganson, K. (2013). Principles of modern operating systems (2nd ed.).Burlington, MA: Jones &Bartlett Learning, LLC.

[86] Avila, M., et al. (2014). Personal communication between Chicago O’Hare International Airport and ICF International, November 13, 2014

[87] Vensim Version 7.3.4 Documentation, Ventana Systems, Inc., https://www.vensim.com/documentation/index.html

[88] G. Hamzawi, Salah. (1992). Lack of airport capacity: Exploration of alternative solutions. Transportation Research Part A: Policy and Practice. 26A. 47-58. 10.1016/0965-8564(92)90044-8.