An heuristic approach for the improvement of aircraft departure scheduling at airports

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AN HEURISTIC APPROACH FOR THE IMPROVEMENT OF AIRCRAFT DEPARTURE SCHEDULING AT AIRPORTS

By
Roberto de Barros Teixeira

A Doctoral Thesis
Submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University of Technology

March 1992

Research Supervisor: Mr Robert Caves,
Director of Research: Professor Norman J. Ashford.

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Declaration of Originality

The work described in this thesis has been carried out by the author except where acknowledged, and has not been submitted, in full or in part, to this or any other institution for a higher degree.
Dedication

I dedicate this work to my wife Edite, who has offered me unflagging support throughout and has provided constant encouragement and inspiration.
SYNOPSIS

AN HEURISTIC APPROACH FOR THE IMPROVEMENT OF AIRCRAFT DEPARTURE SCHEDULING AT AIRPORTS

This work considers the management in the short run of aircraft departures from their parking stands at major airports where traffic congestion is noticeable. At the ground level, congestion is patent when carefully designed departure time tables become unworkable, causing ever increasing delays which penalize heavily passengers, airlines and the airport surrounding community.

The study is composed of two parts:

First an overall analysis of the considered problem is performed to provide background knowledge and to display basic principles for the management of aircraft ground movements at modern airports. Physical components as well as current operational rules are discussed and their interdependence is revealed. A particular importance is given to new and foreseeable developments in communication and guidance technology which allow an improved prediction of runway occupancy times or gaps. Capacity issues are also discussed with respect to aircraft ground activities and the airfield capacity is analysed.

This first part of the work ends with the description of levels of fuel consumption and of pollution emission by aircraft ground operations and thus shows the relevance of the problem considered in this study.

The second part of this work is devoted to the design of a just-in-time clearance policy which should minimise environment, fuel and pollution levels and made possible a delay-free ground traffic for departing aircraft. A mathematical formulation of the considered decision problem, characterized as a real time scheduling problem, is built up. Then possible solution strategies are appraised and an "ad hoc" heuristic solution algorithm is designed. This solution is first compared in theoretical terms with a First Come First Served policy showing that in an error-free situation the proposed solution cannot be worse than its competitor. Then a simulation study is performed which confirms in practical terms the above result. The influence of the main design parameters of the solution algorithm on its performance are also examined giving some insights in relation to necessary communication and prediction aids.

Finally, possible extensions of the proposed method and its integration in a global aircraft traffic management system are discussed.

KEY WORDS:
Airport Operation, Aircraft Scheduling, Heuristic Programing, Cost and Pollution reduction.
ACKNOWLEDGEMENT

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The Brazilian Air Force for sponsoring this research.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Declaration of Originality</td>
<td>I</td>
</tr>
<tr>
<td>Dedication</td>
<td>II</td>
</tr>
<tr>
<td>Synopsis</td>
<td>III</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>IV</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>V</td>
</tr>
<tr>
<td>List of Figures</td>
<td>IX</td>
</tr>
<tr>
<td>List of Tables</td>
<td>XI</td>
</tr>
<tr>
<td>List of Abbreviations</td>
<td>XIII</td>
</tr>
<tr>
<td>List of Symbols</td>
<td>XV</td>
</tr>
<tr>
<td>Chapter 1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Part I</td>
<td></td>
</tr>
<tr>
<td>Chapter 2 Overview of Ground Operations</td>
<td></td>
</tr>
<tr>
<td>2.1 Component Systems Description</td>
<td>7</td>
</tr>
<tr>
<td>2.2 Aircraft Operating Activity at Airports</td>
<td>15</td>
</tr>
<tr>
<td>2.2.1 Departure Activity Sequences</td>
<td>15</td>
</tr>
<tr>
<td>2.2.2 Arrival Activity Sequences</td>
<td>25</td>
</tr>
<tr>
<td>Chapter 3 Communication and Control</td>
<td></td>
</tr>
<tr>
<td>3.1 Introduction</td>
<td>26</td>
</tr>
<tr>
<td>3.2 The Airspace Environment</td>
<td>26</td>
</tr>
<tr>
<td>3.2.1 Airways</td>
<td>26</td>
</tr>
<tr>
<td>3.2.2 Control Zones</td>
<td>27</td>
</tr>
<tr>
<td>3.2.3 Terminal Areas</td>
<td>27</td>
</tr>
<tr>
<td>3.3 Navigation and Communication Aids</td>
<td>27</td>
</tr>
<tr>
<td>3.3.1 VOR/DME</td>
<td>29</td>
</tr>
<tr>
<td>3.3.2 Doppler VOR (DVOR)</td>
<td>30</td>
</tr>
<tr>
<td>3.3.3 Precision Approach Radar (PAR)</td>
<td>30</td>
</tr>
<tr>
<td>3.3.4 Airport Surveillance Radar (ASR)</td>
<td>31</td>
</tr>
</tbody>
</table>
3.3.5 Airport Surface Detection Equipment (ASDE) 31
3.3.6 Instrument Landing System (ILS) 31
3.3.7 Microwave Landing System 31
3.4 Air Traffic Control within Terminal Airspace 32
3.4.1 Instrument Flight Rules Overview 34
3.4.2 Controlling Incoming Aircraft 34
3.4.3 Approach Control 35
3.4.4 Aerodrome Control 36
3.5 Ground Movement Control 36
3.5.1 Controlling Departing Aircraft 37
3.5.2 Ground Guidance Systems 39
3.6 Future Control Processes 40
3.6.1 Time-based Guidance for Air Traffic Control 40
3.6.2 Consequences for ground operations scheduling 42

Chapter 4 Airfield Capacity
4.1 Introduction 45
4.1.1 General definition 45
4.2 Airfield Capacity and Delay 48
4.2.1 Gate Capacity 49
4.2.2 Taxiway Capacity 49
4.2.3 Runway Capacity 50
A) Airport and Air Route Configuration/Facilities 50
B) ATC Methods of Operation 53
C) Traffic Mix and Separations 53
4.3 Operation Rules and Occupancy Times at the Runway 53
4.3.1 Arrivals and Departure Rules 53
4.3.2 Occupancy Time 58
A) Arrival Runway Occupancy 59
B) Departure Runway Occupancy 60
C) Occupancy Times with Mixed Operation 62
4.4 Other Factors Affecting Airfield Capacity 63
4.4.1 Wake Turbulence Separation 63
4.4.2 Weather Conditions 64
4.4.3 Wind shear and crosswinds 64
4.4.4 Low visibility conditions 64
4.4.5 Noise abatement 65
4.5 Measuring the Level of Saturation of an Airfield 66
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.6</td>
<td>Final Observations</td>
<td>67</td>
</tr>
<tr>
<td>Chapter 5</td>
<td>Fuel Consumption and Pollution by Ground Operations</td>
<td></td>
</tr>
<tr>
<td>5.1</td>
<td>Fuel consumption by aircraft ground operations</td>
<td>70</td>
</tr>
<tr>
<td>5.2</td>
<td>Pollutant Emission by Aircraft Ground Operation</td>
<td>75</td>
</tr>
<tr>
<td>5.3</td>
<td>Noise Emission</td>
<td>75</td>
</tr>
<tr>
<td>5.4</td>
<td>Fuel Conservation Practices and Procedure</td>
<td>80</td>
</tr>
<tr>
<td>5.4.1</td>
<td>Current Practices for ground operations</td>
<td>80</td>
</tr>
<tr>
<td>A)</td>
<td>Starting Engines during pushback</td>
<td>80</td>
</tr>
<tr>
<td>B)</td>
<td>Taxiing out or in with one or more engines shut-down</td>
<td>82</td>
</tr>
<tr>
<td>5.4.2</td>
<td>Towing of aircraft between terminal area and runways</td>
<td>88</td>
</tr>
<tr>
<td>5.4.3</td>
<td>Planning landing roll turn-off and taxiing</td>
<td>90</td>
</tr>
<tr>
<td>5.4.4</td>
<td>Gate hold procedures</td>
<td>91</td>
</tr>
<tr>
<td>Part II</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chapter 6</td>
<td>Mathematical Formulation of the Ground Scheduling Problem</td>
<td></td>
</tr>
<tr>
<td>6.1</td>
<td>Introduction</td>
<td>93</td>
</tr>
<tr>
<td>6.2</td>
<td>A Global Model</td>
<td>93</td>
</tr>
<tr>
<td>6.2.1</td>
<td>The Structure of the Terminal System</td>
<td>94</td>
</tr>
<tr>
<td>6.2.2</td>
<td>The Global Objectives Function</td>
<td>94</td>
</tr>
<tr>
<td>6.2.3</td>
<td>Decision Variables and Restrictions</td>
<td>96</td>
</tr>
<tr>
<td>6.2.4</td>
<td>Complexity of the Global Optimisation Problem</td>
<td>102</td>
</tr>
<tr>
<td>6.3</td>
<td>An Optimisation Approach for the Departing Scheduling Problem</td>
<td>103</td>
</tr>
<tr>
<td>6.3.1</td>
<td>Mathematical Formulation of the Departing Scheduling Problem</td>
<td>103</td>
</tr>
<tr>
<td>6.3.2</td>
<td>Analysis of the Departing Scheduling Problem (DSP)</td>
<td>105</td>
</tr>
<tr>
<td>6.3.3</td>
<td>Exact Solution Methods for the DSP</td>
<td>106</td>
</tr>
<tr>
<td>A)</td>
<td>Backtrack Programming</td>
<td>106</td>
</tr>
<tr>
<td>B)</td>
<td>Branch and Bound Programming</td>
<td>107</td>
</tr>
<tr>
<td>6.4</td>
<td>Approximate Solution for the DSP</td>
<td>109</td>
</tr>
<tr>
<td>6.4.1</td>
<td>Greedy Solution Approaches</td>
<td>109</td>
</tr>
<tr>
<td>Chapter 7</td>
<td>An Heuristic Approach for On-line Scheduling of Departing Aircraft</td>
<td></td>
</tr>
<tr>
<td>7.1</td>
<td>The Basic Idea</td>
<td>114</td>
</tr>
<tr>
<td>7.2</td>
<td>Selection of the Instants of Decision</td>
<td>115</td>
</tr>
<tr>
<td>7.3</td>
<td>Selection of the span of optimization Horizon</td>
<td>117</td>
</tr>
<tr>
<td>7.4</td>
<td>Determination of the mean pattern of Gaps</td>
<td>119</td>
</tr>
<tr>
<td>7.5</td>
<td>The Objective Function</td>
<td>122</td>
</tr>
<tr>
<td>7.6</td>
<td>The real-time Decision Sequence</td>
<td>124</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure No.</th>
<th>TITLE</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>The Airport System</td>
<td>8</td>
</tr>
<tr>
<td>2.2</td>
<td>Terminal Configuration</td>
<td>10</td>
</tr>
<tr>
<td>2.3</td>
<td>Aircraft Parking Positions</td>
<td>11</td>
</tr>
<tr>
<td>2.4</td>
<td>Methods of Taxiing out from a Parked Position.</td>
<td>12</td>
</tr>
<tr>
<td>2.5</td>
<td>Ground Service Around Transit Aircraft</td>
<td>13</td>
</tr>
<tr>
<td>2.6</td>
<td>Stands Exit and Entry Aircraft Manouver</td>
<td>14</td>
</tr>
<tr>
<td>2.7</td>
<td>An Example of Runway and Departure Routes</td>
<td>16</td>
</tr>
<tr>
<td>2.8</td>
<td>Departure Activity Events Sequency</td>
<td>21</td>
</tr>
<tr>
<td>2.9</td>
<td>Arrival Activity Events Sequency</td>
<td>24</td>
</tr>
<tr>
<td>3.1</td>
<td>Rio de Janeiro Terminal Area</td>
<td>28</td>
</tr>
<tr>
<td>3.2</td>
<td>Comparative Diagram ILS -MLS</td>
<td>33</td>
</tr>
<tr>
<td>4.1</td>
<td>Relationship Between Delay and Capacity</td>
<td>47</td>
</tr>
<tr>
<td>4.2</td>
<td>Taxiway and Runway Entry</td>
<td>51</td>
</tr>
<tr>
<td>4.3</td>
<td>Time-Distance Diagram for two approaching and one Departing Aircraft</td>
<td>52</td>
</tr>
<tr>
<td>4.4</td>
<td>Achieving the Optimum Interleaving of Departure into the Arrival Stream</td>
<td>54</td>
</tr>
<tr>
<td>4.5</td>
<td>Rates of Arrivals and Departures</td>
<td>68</td>
</tr>
<tr>
<td>6.1</td>
<td>Structure of the Terminal System</td>
<td>95</td>
</tr>
<tr>
<td>6.2</td>
<td>Holding Policy</td>
<td>97</td>
</tr>
<tr>
<td>6.3</td>
<td>Cost of a Departure Delay</td>
<td>98</td>
</tr>
<tr>
<td>6.4</td>
<td>Position of Aircraft</td>
<td>101</td>
</tr>
<tr>
<td>6.5</td>
<td>Search Tree for Backtrack</td>
<td>108</td>
</tr>
<tr>
<td>6.6</td>
<td>Branch and Bound Search Tree</td>
<td>111</td>
</tr>
<tr>
<td>6.7</td>
<td>Simplified Structure</td>
<td>113</td>
</tr>
<tr>
<td>Figure No.</td>
<td>TITLE</td>
<td>Page</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>7.1</td>
<td>Non Interaction Principle</td>
<td>116</td>
</tr>
<tr>
<td>7.2</td>
<td>Selection of Decision Times</td>
<td>118</td>
</tr>
<tr>
<td>7.3</td>
<td>Definition of the Span of Optimization</td>
<td>120</td>
</tr>
<tr>
<td>7.4</td>
<td>Penalty for using Stand(i)</td>
<td>125</td>
</tr>
<tr>
<td>7.5</td>
<td>Real Time Decision Sequence</td>
<td>127</td>
</tr>
<tr>
<td>7.6</td>
<td>Minimum Separation Constraints</td>
<td>128</td>
</tr>
<tr>
<td>7.7</td>
<td>Non Conflicting Rolling out Manoeuvens</td>
<td>130</td>
</tr>
<tr>
<td>7.8</td>
<td>Gap Update Condition</td>
<td>131</td>
</tr>
<tr>
<td>7.9</td>
<td>Local Optimum Ordering of Flight</td>
<td>133</td>
</tr>
<tr>
<td>7.10</td>
<td>Example of Search for the best Solution</td>
<td>135</td>
</tr>
<tr>
<td>7.11</td>
<td>Example of General Airfield Configuration</td>
<td>136</td>
</tr>
<tr>
<td>8.1(a)</td>
<td>The Program Structure (Part I)</td>
<td>141</td>
</tr>
<tr>
<td>8.1(b)</td>
<td>The Program Structure (Part II)</td>
<td>142</td>
</tr>
<tr>
<td>8.2</td>
<td>Evolution of Mean Delays from Proposed Heuristic Methodology</td>
<td>147</td>
</tr>
<tr>
<td>8.3</td>
<td>Mean Delay Standard Deviation Evolution with Traffic</td>
<td>149</td>
</tr>
<tr>
<td>8.4</td>
<td>Influence of the Duration of the Decision Time Window</td>
<td>150</td>
</tr>
<tr>
<td>8.5</td>
<td>Average Delay Influence of DTW Duration</td>
<td>151</td>
</tr>
<tr>
<td>8.6</td>
<td>Influence of Taxiing Duration</td>
<td>153</td>
</tr>
<tr>
<td>8.7</td>
<td>Mean Delay Resulting from FCFS and Heuristic Schedules</td>
<td>154</td>
</tr>
<tr>
<td>8.8</td>
<td>Comparison of Fuel Cost Resulting from FCFS and Heuristic Schedules.</td>
<td>156</td>
</tr>
</tbody>
</table>
# List of Tables

<table>
<thead>
<tr>
<th>Table No.</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Basic Runway Configurations</td>
<td>17</td>
</tr>
<tr>
<td>2.2</td>
<td>Weight Parameters</td>
<td>18</td>
</tr>
<tr>
<td>2.3</td>
<td>Typical Time in Node for Landing - Takeoff Cycle at a Metropolitan Airport</td>
<td>19</td>
</tr>
<tr>
<td>2.4</td>
<td>Operating Time, Minutes for Engine Start Activity</td>
<td>22</td>
</tr>
<tr>
<td>3.1</td>
<td>Taxi Guidance</td>
<td>43</td>
</tr>
<tr>
<td>4.1</td>
<td>Departure Track Separation Criteria</td>
<td>57</td>
</tr>
<tr>
<td>5.1</td>
<td>Aircraft Classification</td>
<td>71</td>
</tr>
<tr>
<td>5.2(a)</td>
<td>Fuel Flow Rates</td>
<td>72</td>
</tr>
<tr>
<td>5.2(b)</td>
<td>Fuel Flow Rates</td>
<td>73</td>
</tr>
<tr>
<td>5.3</td>
<td>Fuel Consumption Under Taxi Conditions</td>
<td>74</td>
</tr>
<tr>
<td>5.4(a)</td>
<td>Modal Emission Factors</td>
<td>76</td>
</tr>
<tr>
<td>5.4(b)</td>
<td>Modal Emission Factors</td>
<td>77</td>
</tr>
<tr>
<td>5.4(c)</td>
<td>Modal Emission Factors</td>
<td>78</td>
</tr>
<tr>
<td>5.5</td>
<td>Emission Factors and Fuel Consumption Factors by Aircraft type</td>
<td>79</td>
</tr>
<tr>
<td>5.6</td>
<td>Effect of Engine Start Procedure on Hold Before Taxi</td>
<td>81</td>
</tr>
<tr>
<td>5.7</td>
<td>Potential Fuel Savings Starting Engines During Pushback DCA</td>
<td>83</td>
</tr>
<tr>
<td>5.8</td>
<td>Potential and Actual Annual Fuel Savings due to taxiing on less than all Engines at DCA</td>
<td>85</td>
</tr>
<tr>
<td>5.9(a)</td>
<td>Potential and Actual Annual Fuel Savings due to taxiing on less than all Engines at IAD</td>
<td>86</td>
</tr>
<tr>
<td>5.9(b)</td>
<td>Potential and Actual Annual Fuel Savings due to taxiing on less than all Engines at IAD</td>
<td>87</td>
</tr>
<tr>
<td>5.10</td>
<td>Consumption Rates</td>
<td>91</td>
</tr>
<tr>
<td>8.1</td>
<td>Minimum Inter-Arrival Times</td>
<td>144</td>
</tr>
<tr>
<td>8.2</td>
<td>Minimum Inter-Departure Times</td>
<td>145</td>
</tr>
<tr>
<td>Table No.</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>-----------</td>
<td>--------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>8.3</td>
<td>Gaps Distribution at the Runway</td>
<td>157</td>
</tr>
<tr>
<td>8.4(a)</td>
<td>Initial Weights for Departing Aircraft</td>
<td>158</td>
</tr>
<tr>
<td>8.4(b)</td>
<td>Initial Weights for Departing Aircraft</td>
<td>159</td>
</tr>
<tr>
<td>8.5(a)</td>
<td>Desired and Effective Departure Time (Heuristic)</td>
<td>160</td>
</tr>
<tr>
<td>8.5(b)</td>
<td>Desired and Effective Departure Time (Heuristic)</td>
<td>161</td>
</tr>
<tr>
<td>8.6(a)</td>
<td>Delay from FCFS and Heuristic Techniques</td>
<td>163</td>
</tr>
<tr>
<td>8.6(b)</td>
<td>Delay from FCFS and Heuristic Techniques</td>
<td>164</td>
</tr>
</tbody>
</table>
## LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4D</td>
<td>Four Dimensional</td>
</tr>
<tr>
<td>AD</td>
<td>Average Delay</td>
</tr>
<tr>
<td>APU</td>
<td>Auxiliar Power Unit</td>
</tr>
<tr>
<td>ASDE</td>
<td>Airport Surface Detection Equipment</td>
</tr>
<tr>
<td>ASP</td>
<td>Arrival Scheduling Problem</td>
</tr>
<tr>
<td>ASR</td>
<td>Airport Surveillance Radar</td>
</tr>
<tr>
<td>ATC</td>
<td>Air Traffic Control</td>
</tr>
<tr>
<td>ATCC</td>
<td>Air Traffic Control Center</td>
</tr>
<tr>
<td>CENA</td>
<td>Centre d'Etudis de la Navigation Aerienne</td>
</tr>
<tr>
<td>CTZ</td>
<td>Control Zone</td>
</tr>
<tr>
<td>DCA</td>
<td>Washington National Airport</td>
</tr>
<tr>
<td>DME</td>
<td>Distance Measuring Equipment</td>
</tr>
<tr>
<td>DSP</td>
<td>Departure Scheduling Problem</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
</tr>
<tr>
<td>FC</td>
<td>Fuel Consumed</td>
</tr>
<tr>
<td>FCFS</td>
<td>First Come First Served</td>
</tr>
<tr>
<td>FFR</td>
<td>Fuel Flow Rate</td>
</tr>
<tr>
<td>FT</td>
<td>Full Thrust</td>
</tr>
<tr>
<td>GPU</td>
<td>Ground Power</td>
</tr>
<tr>
<td>IAD</td>
<td>Dulles International Airport</td>
</tr>
<tr>
<td>ICAO</td>
<td>International Civil Aviation Organization</td>
</tr>
<tr>
<td>IFR</td>
<td>Instrument Flight Rules</td>
</tr>
<tr>
<td>ILS</td>
<td>Instrument Landing System</td>
</tr>
<tr>
<td>INS</td>
<td>Inertial Navigation</td>
</tr>
<tr>
<td>KBS</td>
<td>Knowledge Based Computer System</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>MLS</td>
<td>Microwave Landing System</td>
</tr>
<tr>
<td>NOPS</td>
<td>Number of Operation</td>
</tr>
<tr>
<td>NP</td>
<td>Non Polynomial</td>
</tr>
<tr>
<td>P</td>
<td>Polynomial</td>
</tr>
<tr>
<td>PAR</td>
<td>Precision Approach Radar</td>
</tr>
<tr>
<td>ROT</td>
<td>Runway Occupancy Time</td>
</tr>
<tr>
<td>SD</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>SSR</td>
<td>Secondary Surveillance Radar</td>
</tr>
<tr>
<td>TIM</td>
<td>Time in Mode</td>
</tr>
<tr>
<td>TMA</td>
<td>Terminal Control Area</td>
</tr>
<tr>
<td>TOD</td>
<td>Top of Descent</td>
</tr>
<tr>
<td>TWD</td>
<td>Total Weight Delay</td>
</tr>
<tr>
<td>VOR</td>
<td>VHF Omnidirectional Range</td>
</tr>
</tbody>
</table>
### LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>Time - period considered</td>
</tr>
<tr>
<td>$N_a$</td>
<td>Number of arriving aircraft</td>
</tr>
<tr>
<td>$N_d$</td>
<td>Number of departing aircraft</td>
</tr>
<tr>
<td>$C^k_a$</td>
<td>Cost of a delay of one unit of time for the $k^{th}$ arriving aircraft</td>
</tr>
<tr>
<td>$C^k_t$</td>
<td>Cost of one unit of time for the $k^{th}$ arriving aircraft</td>
</tr>
<tr>
<td>$C_f^h$</td>
<td>Value of the fuel burned by the $h^{th}$ departing aircraft</td>
</tr>
<tr>
<td>$C_d^h$</td>
<td>Cost of a departure delay for the $h^{th}$ departing aircraft</td>
</tr>
<tr>
<td>$t^k_a$</td>
<td>Delay incurred by the $k^{th}$ arriving aircraft</td>
</tr>
<tr>
<td>$t^h_d$</td>
<td>Delay incurred by the $h^{th}$ departing aircraft</td>
</tr>
<tr>
<td>$T^k_a$</td>
<td>Desired arrival time for the $k^{th}$ arriving aircraft</td>
</tr>
<tr>
<td>$t^h_a$</td>
<td>Assigned arrival time for the $k^{th}$ arriving aircraft</td>
</tr>
<tr>
<td>$T^h_d$</td>
<td>Desired departure time for the $h^{th}$ departing aircraft</td>
</tr>
<tr>
<td>$t_d^h$</td>
<td>Assigned departure time for the $h^{th}$ departing aircraft</td>
</tr>
<tr>
<td>$S_{aa}^{kk}$</td>
<td>Minimum separations between arrivals</td>
</tr>
<tr>
<td>$S_{dd}^{hh}$</td>
<td>Minimum separations between departures</td>
</tr>
<tr>
<td>$S_{dd}^{hh}$</td>
<td>Minimum separations between arrivals and departures</td>
</tr>
<tr>
<td>$S_{dd}^{kk}$</td>
<td>Minimum separations between departures and arrivals</td>
</tr>
<tr>
<td>$S_{dd}^{hh}$</td>
<td>Minimum separations taking into account minimum time separation between aircraft of given categories and standard minimum distance</td>
</tr>
<tr>
<td>$E$</td>
<td>Runway threshold</td>
</tr>
<tr>
<td>$I_k$</td>
<td>Entry gate for the $k^{th}$ arriving aircraft</td>
</tr>
<tr>
<td>$O_h$</td>
<td>Exit gate for the $h^{th}$ departing aircraft</td>
</tr>
<tr>
<td>$t_e^h$</td>
<td>Instant at which $h^{th}$ aircraft leaves the TMA at gate $O_h$</td>
</tr>
</tbody>
</table>
CHAPTER ONE

INTRODUCTION

1.1 Problem Description

With the continuous increase of air transportation in these last decades, terminal airspace and landspace at major airports has become more and more saturated. This has resulted in large delays being suffered both by passengers and airlines. It has been recognized that if no action is taken the whole air transportation activity will collapse despite a continuing strong demand for services.

While for the airborne part of flight many efforts have been made at national and international levels to design efficient Air Traffic Control (ATC) systems with the primary objective of ensuring air security and capacity, much less has been done until recently to optimize effectively the ground traffic at airports.

Traditionally airlines negotiate with airport authorities time tables for their regulated traffic well in advance, while for unregulated flights, this negotiation takes place no less than half an hour before the earliest desired time for departure. Also, meetings for the Coordination of Timetables have been held in the IATA framework for several years. The initial purpose of these informal meetings was to smooth out interline connections and handling arrangements. The enforcement of night curfews in Europe, Hong Kong, Japan and Australia, as well as the beginning of traffic congestion at major European airports has grown so much that the negotiation of schedule adjustments to meet airport capacity limitations outside the USA has become the main task of the 400 participants who now attend the Timetables Meetings, representing 135 scheduled and non-scheduled airlines. The operational and commercial impact of current and possible future limitations on airline schedules is a key issue for this Conference.

Another aspect concerns slot allocations at busy airports. To accommodate new entrants there may be provisions for lotteries. Furthermore, in USA airlines with domestic slots at any of these airports are free to buy and sell
them as they wish. While slots for international carriers are not affected by these arrangements because they would be in conflict with obligations under most bilateral air service agreements.

Meanwhile, either runway gaps are allocated or not on a slot basis, the ultimate decision for departure is taken in general by the airport ground control team (tower). This decision, clearance for leaving the parking stand, is actually taken on an empirical basis considering slot allocation (when this technique is used) and taxi delays. Thus, in the short run, controllers tend to use a first come first served - FCFS policy based either on the slot allocation table or on the sequence of solicitations for departures.

However, the main difficulty for the management of ground traffic in the short run is dependent on the stochastic nature of the availability of runways for take-off since arriving aircraft have priority of use for landing and of the availability of runways (standard minimum separation). Thus, today aircraft engaged in the cycle of departure activities with engines already running suffer repeated additional delays and costs: delays at taxiway intersections, exits of maneuver areas and queues at runway thresholds. These additional costs which are suffered by airlines have been increasing with the growing saturation of airports and their suppression constitutes now an important source of fuel economy. Also, airport authorities have become more and more concerned with environmental issues and they consider that the suppression of this source of additional pollution is wholly desirable objective.

Thus, the management of departures the short run appears to be a relevant question which is not answered satisfactorily until now.

1.2 Scope of the Research

Today with the simultaneous development of efficient automation sequences for on line air traffic management systems for inbound flights and of new avionics navigation and guidance systems, accurate four dimensional (4D) guidance through whole air terminal areas until touchdown has become a reality. So the real time management of runway and airways occupancy is now technically possible.
Concerned with the improvement of ground activities at airports and more specifically with the problem of scheduling departing aircraft under 4D guidance, this research investigates the feasibility of a just-in-time clearance policy which will avoid any delay after departure from the parking stands by aircraft with engines on. Thus a decision problem in a real time environment must be formulated with the consideration of quantitative decision criteria and operational constraints which rise and vanish as time flows.

The Operations Research literature is rich of studies for this class of decision problems timed as "real-time scheduling problems". Many applications in different fields of human activity are reported and solution approaches have been assessed. In general no exact solution is at hand either for lack of data over future events or for the computational burden to get it which forbids a real time result. Then heuristic techniques have been designed in a case to case basis.

Here the management of departures is tackled as a real-time scheduling problem and an heuristic solution technique is designed for this case. This solution technique is characterized by the use of data proceeding from new communication and prediction aids and a computer algorithm is built to run it.

This proposed solution is carefully analysed. In particular, the influence of different design parameters over its performance, is assessed. Then this solution is compared through a simulation study with a FCFS policy which is representative of current practice.

Since the proposed solution appears to be superior to current practice, its practical feasibility is discussed and operations rules to cope with error predictions are considered.

1.3 Structure of the Thesis
This thesis is composed of two parts:

- Part I provides an overview of the whole problem considered, while
Part II is relative to the mathematical formulation of the scheduling problem, its solution and the evaluation of the proposed method.

Part I
The first five chapters are concerned with background knowledge and basic principles of the important issues, which serve as a prelude to the description of methodology.

Chapter two presents an overview of aircraft operating activities in modern airports, the first part briefly covering the physical components of the airport, and the second part discussing the operational rules used to manage aircraft arriving and departing ground movements. This chapter displays the complexity of the problem and the integration of technology and operational rules necessary to solve it.

Chapter three presents a survey of the communication and control aids used for guidance of aircraft during airport ground operations, and in the near air-space. A particular attention is given to new developments in communication technology which are liable to favour new operations procedures for aircraft ground movements.

Chapter four considers the ability of an airfield to deliver acceptable levels of service with respect to aircraft ground activities. The runway and airfield capacity concepts are presented and analysed with great care particularly with respect to induced delays either at departure or arrival. The proposed method for scheduling departing aircraft should decrease their service time and so, improve the capacity of the airfield.

Chapter five is concerned with fuel consumption and pollution emission by ground operations. This chapter shows clearly the relevance of the problem and its importance not only for the economy of airlines or for the comfort of passengers, but also for the preservation of the environment in regions which are always at proximity of urban areas.
Part II
The remaining chapters are directly related to the methodological development of what must be considered as a decision problem.

Chapter six provides a detailed description of a mathematical programming approach of the Departure scheduling Problem. The proposed decision problem is identified as a Non Polynomial - complete one and possible solution strategies are discussed. Basic characteristics for a feasible solution strategy are established. This solution strategy should cope with a very large number of candidate solutions in a real time context.

Chapter seven is directly related to the methodology in consideration, and gives a detailed description of an Heuristic approach for on-line scheduling of departing aircraft. This description includes the proposed quadratic criterion which allows the integration of actual delays and classes of aircraft in a global performance index and the operations constraints which must be satisfied by the solution. The decision process is then described. The sub-optimality of the proposed scheduling algorithm is carefully analysed and compared with a first come first served (FCFS) scheduling algorithm currently adopted. It is shown that for specific conditions, the proposed solution can not be worse, in terms of delays, than the FCFS solution. It is worth noting here that delays in a FCFS policy are incurred by aircraft with engines on while in the proposed solution delayed aircraft are with their engines off.

Chapter eight displays the preliminary application of the heuristic scheduling algorithm proposed in chapter seven for the management of departing aircraft. The influence of various design parameters for the proposed solution are appraised in this simulation study. The influence of the level of saturation of the runway, of the ratio between arrivals and departures and of the distribution of classes of aircraft are displayed and analysed.
Finally a comparative study is performed between the proposed solution and a FCFS policy. Simulation results show clearly the pre-eminence of the heuristic solution.

Chapter nine summarises the conclusions and the significance of adopting this methodology, and provides some recommendations for further research.
CHAPTER TWO

OVERVIEW OF GROUND OPERATIONS

This chapter presents an overview of aircraft operating activities in modern airports. These activities are characterised by two elements:

- The physical components of the airfield system at the airport,
- The operation rules used to manage aircraft arriving and departing ground movements.

2.1 Component Systems Description.
The airport components of interest here are those which interact with the ground movement of aircraft (The Airport Air Side - Figure 2.1). Areas such as:

- terminal airspace, runways, taxiways, parking areas (apron), access, exit points and forbidden areas, airport facilities ...

The size, configuration and number of each of these elements and their relative position will be a strong component of the management problem of aircraft ground traffic. Another important factor is relative to the size, manoeuvrability and mix of operated aircraft.

Nowadays no standard configuration exists for the organization of the airfield of modern airports. This can be explained by the fact that each airport obeys particular constraints (demand, geographical, position, meteorological) which even if common solution principles are used, leads to different solutions. So a very important diversity of configurations is found among larger airports around the world, even within individual countries (USA, some European country, Brazil, China, ...).
Figure 2-1  The Airport System.
The terminal design represents the configuration of the terminal / apron (landside/airside) interface, which is the airside concourse of the terminal. There are no clear and distinct definitive types of design concepts that could be traced in literature, where each reference traced named and classified concepts upon personal discretion:

Horonjeff* classified them as: gate arrival, pier finger, pier satellite, remote satellite, and mobile conveyance.

IATA** classification is: pier/central, satellite/central, linear, transporter, and unit terminal.

ICAO*** classification is: simples, linear, finger, satellite, and others (inter alia) - mobile lounge, and unit terminal.

Ashford**** classified them into: open apron or linear, central/pier finger, central/pier satellite, central/remote satellite, remote apron, remote pier, and unit terminals. And in the same reference full detail about Parking configurations, servicing equipment maneuvering for pushout and taxiout angle configurations.

Figure 2.2 displays some possible models for apron organization while Figure 2.3 displays various parking tactical positions for aircraft with respect to fingers.

Figure 2.4 shows methods of taxiing out from a parked position. Figure 2.5 gives a detailed view of ground services around transit aircraft.

Possible access and exit ways to stand areas, either through autonomous means or pushback devices, are represented in Figure 2.6.

(*) Horonjeff, 1983.


(****) Ashford & Wright, 1984.
Figure 2-2 Terminal configurations.
Figure 2-3  Aircraft Parking Position.
Clearance $F$ is straight out taxi with the aircraft turning at the most critical distance. Clearance $A$ is obtained when no turn is initiated, and is 4.5' more than $F$.

Figure 2-4 Methods of taxiing out from a parked position.
Figure 2-5  Ground service around transit aircraft.
Figure 2-6  Stands exit and entry aircraft maneuver.
Runways configuration can be categorized according to runway use and runway interaction with taxiways and air routes. Table 2.1 displays 13 different categories from the simple single runway to multiple runway alignments in use concurrently. Also departure routes may have an important influence on departure capacity and delays. Figure 2.7 displays an example of different combined runway and departure routes.

With respect to ground operations, aircraft can be classified in different ways according to the considered aspect. Criteria of classification could be:
- size of aircraft,
- weight of aircraft,
- generated wake vortex,
- engine configuration (with consequences for the exhaust influence area),
- nominal taxiway speed,
- runway occupancy time at landing or take-off
- ground manoeuvrability and autonomy.

For instance, with respect to wake vortex ICAO and UK authorities defines the well know categories displayed an Table 2.2.

In Table 2.3 typical times for different kinds of aircraft are displayed showing large discrepancies between airlines, general aviation and military aircraft.

2.2 Aircraft Operating Activities at Airports
This section presents an overview of classical aircraft operating activities at airports. The section is divided into two subsections - departure activities and arrival activities.

2.2.1 Departure Activity Sequences
At some major airports when an aircraft is ready for departure, the pilot contacts the tower. If it is a regular flight it has been allocated a departure slot. This will be confirmed and an airways clearance will be given. Although initial slot allocation is negotiated directly between the operator and the
Figure 2-7  An example of runway and departure routes.
### Table 2.1 Basic Runway Configurations

<table>
<thead>
<tr>
<th>Configuration Code and Type</th>
<th>Diagram</th>
<th>Number of Access Points</th>
<th>Number of Runways</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Single</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Two Parallel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Close</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>b. Intermediate</td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>c. Far</td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3. Three Parallel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Close/Close</td>
<td></td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>b. Close/Intermediate</td>
<td></td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>c. Far</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4. Four Parallel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Close/Intermediate/Close</td>
<td></td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>b. Close/Far/Close</td>
<td></td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>c. Intermediate/Far/Intermediate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Single Intersecting</td>
<td></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>a. Between Thresholds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. Beyond Thresholds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Single/Two Parallel Intersecting</td>
<td></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>a. Between Thresholds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. Beyond Thresholds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Double/Two Parallel Intersecting</td>
<td></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>a. Between Thresholds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. Beyond Thresholds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Single Open V</td>
<td></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>9. Single/Two Parallel Open V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. Double/Two Parallel Open V</td>
<td></td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>11. Dual Lane</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Single</td>
<td></td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>b. Independent Two Parallel</td>
<td></td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>c. Independent Four Parallel</td>
<td></td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>12. Special Purpose (STOL, etc.)</td>
<td>n.a.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13. Complex</td>
<td></td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Category</td>
<td>I.C.A.O. and flight plan</td>
<td>U.K.</td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>--------------------------</td>
<td>------------</td>
<td></td>
</tr>
<tr>
<td>Heavy (H)</td>
<td>136 000 or greater</td>
<td>136 000 or greater</td>
<td></td>
</tr>
<tr>
<td>Medium (M)</td>
<td>Less than 136 000 and more than 7 000</td>
<td>Less than 136 000 and more than 40 000</td>
<td></td>
</tr>
<tr>
<td>Small (S)</td>
<td></td>
<td>Less than 40 000 and more than 17 000</td>
<td></td>
</tr>
</tbody>
</table>

(All weights are in Kilograms).

Table 2.2 Weight parameters
<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Taxi-idle outbound</th>
<th>Take-off</th>
<th>Climbout</th>
<th>Approach</th>
<th>Taxi-idle inbound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jumbo jet</td>
<td>19.00</td>
<td>0.70</td>
<td>2.20</td>
<td>4.00</td>
<td>7.00</td>
</tr>
<tr>
<td>Long range jet</td>
<td>19.00</td>
<td>0.70</td>
<td>2.20</td>
<td>4.00</td>
<td>7.00</td>
</tr>
<tr>
<td>Medium range jet</td>
<td>19.00</td>
<td>0.70</td>
<td>2.20</td>
<td>4.00</td>
<td>7.00</td>
</tr>
<tr>
<td>Air carrier turboprop</td>
<td>19.00</td>
<td>0.50</td>
<td>2.50</td>
<td>4.50</td>
<td>7.00</td>
</tr>
<tr>
<td>Business jet</td>
<td>6.50</td>
<td>0.40</td>
<td>0.50</td>
<td>1.60</td>
<td>6.50</td>
</tr>
<tr>
<td>General aviation turboprop</td>
<td>19.00</td>
<td>0.50</td>
<td>2.50</td>
<td>4.50</td>
<td>7.00</td>
</tr>
<tr>
<td>General aviation piston</td>
<td>12.00</td>
<td>0.30</td>
<td>4.98</td>
<td>6.00</td>
<td>4.00</td>
</tr>
<tr>
<td>Piston transport</td>
<td>6.50</td>
<td>0.60</td>
<td>5.00</td>
<td>4.60</td>
<td>6.50</td>
</tr>
<tr>
<td>Helicopter</td>
<td>3.50</td>
<td>0</td>
<td>6.50</td>
<td>6.50</td>
<td>3.50</td>
</tr>
<tr>
<td>Military transport</td>
<td>19.00</td>
<td>0.50</td>
<td>2.50</td>
<td>4.50</td>
<td>7.00</td>
</tr>
<tr>
<td>Military jet</td>
<td>6.50</td>
<td>0.40</td>
<td>0.50</td>
<td>1.60</td>
<td>6.50</td>
</tr>
<tr>
<td>Military piston</td>
<td>6.50</td>
<td>0.60</td>
<td>5.00</td>
<td>4.60</td>
<td>6.50</td>
</tr>
</tbody>
</table>

Table 2.3  Typical Time in Mode For Landing-Takeoff Cycle at a Metropolitan Airport.

Air Traffic Control Centre (ATCC), any changes required up to 30 minutes before departure have to be negotiated via the tower.

After slot confirmation, airways clearance and start-up clearance, the departing aircraft requests clearance to enter the taxiway system.

Figure 2.8 shows a generalized departure activity sequence beginning with operations at the gate. Gate operations are terminated after a clearance to pushback is obtained from the tower. It is noted that aircraft can hold at a gate if delays are expected; however, normally aircraft are pushed back from the gate when the pushback clearance is received in order to release the gate for arriving aircraft.

Aircraft are pushed back from gates located in congested areas to areas where engines can be operated without producing a jet blast hazard for nearby personnel, equipment, or aircraft. Pushback distances vary from a few feet to 200 or 300 feet at Washington National. The pushback operation is completed when pushback vehicles are disconnected and the pushback crew gives the all clear signal to the pilot. Aircraft are not pushed back in airports where passengers are transported in mobile lounges from passenger gates to the aircraft. Aircraft then taxi from a remote parked position.

Engines may be started at various stages as it is shown in the (Fig.2.8) by the dashed lines. They may be started at the stand (gate), during push-back (except for icy conditions) or after the push-back activity is completed.

An engine start cycle can be completed in 30 to 45 seconds. The second engine can be started before the first cycle is completed and is often begun about 30 seconds after the cycle on the preceding engine was initiated. But, the second start cycle can be commenced within 15 to 20 seconds.

(*) Engines are sometimes started on APU equipped aircraft before the aircraft is pushed away from the gate because the APU is not performing satisfactorily and an air start unit is needed to start the first engine.
<table>
<thead>
<tr>
<th>ACTIVITY-EVENT</th>
<th>TIME SEQUENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stand</td>
</tr>
<tr>
<td>Gate Operation &amp; Hold;</td>
<td></td>
</tr>
<tr>
<td>Slot allocation</td>
<td></td>
</tr>
<tr>
<td>(no regular);</td>
<td></td>
</tr>
<tr>
<td>Request Pushback clearance;</td>
<td></td>
</tr>
<tr>
<td>Start-up;</td>
<td></td>
</tr>
<tr>
<td>Pushback from Gate</td>
<td></td>
</tr>
<tr>
<td>Disconnect tow vehicle</td>
<td></td>
</tr>
<tr>
<td>Start engines</td>
<td></td>
</tr>
<tr>
<td>Request clearance to taxi</td>
<td></td>
</tr>
<tr>
<td>Hold before taxi</td>
<td></td>
</tr>
<tr>
<td>Taxi to Departure queue</td>
<td></td>
</tr>
<tr>
<td>Hold at control point</td>
<td></td>
</tr>
<tr>
<td>Tower clearance to proceed</td>
<td></td>
</tr>
<tr>
<td>Queue in Dep. line</td>
<td></td>
</tr>
<tr>
<td>Tower clearance to proceed</td>
<td></td>
</tr>
<tr>
<td>Move to line-up position</td>
<td></td>
</tr>
<tr>
<td>Take-off roll</td>
<td></td>
</tr>
<tr>
<td>Airborne time</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2-8  Departure Activity Events Sequence.**

Ref. FAA-EE-82-8
<table>
<thead>
<tr>
<th>Engine Start Cycle as appropriate for Aircraft</th>
<th>Operating Time on Started Engines, Minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>One Engine Aircraft</td>
</tr>
<tr>
<td>First Start</td>
<td>1</td>
</tr>
<tr>
<td>Second Start</td>
<td>0</td>
</tr>
<tr>
<td>Third Start</td>
<td>0</td>
</tr>
<tr>
<td>Fourth Start</td>
<td>0</td>
</tr>
<tr>
<td>Total Engine Operating Time</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2.4 Operating time, Minutes for Engine Start Activity.

Ref. FAA-EE-82-8
Table 2.4 shows operating times for each engine and for all engines for start cycles beginning every 30 seconds and completed in 60 seconds. Operating time shown for the first engine started is the time that would elapse before all engines started are ready to taxi. The total amount of operating time on each and on all engines is shown for each completed start cycle.

Tower clearance may be received immediately after request or may be delayed when the ground control communications channel is congested or when other traffic activities are present in the vicinity. In addition, the pilot may delay his clearance request for departure to avoid a long queue at the taxiway hold point.

Aircraft taxis from the stand or parked positions along designated taxi routes to the departure holding point. They approach along an engine run up area where several aircraft may wait for final clearance to take-off. Final pre-flight checks are completed in this area by the crew. Run-up areas should be wide enough in most instances to permit overtaking by leaving aircraft over delayed aircraft. An airport may have more than one outbound taxiway to the runway departure point. In addition, take-offs may be made from more than one point along runways.

Alternative taxiway approaches, to the departure point, may be used as holding stations for aircraft being delayed for some en route capacity problems since it is necessary to free the stands for arriving traffic.

The time needed to taxi from the stand (gate) to the active runway consists of:

- time to taxi,
- time associated with holding at control points such as intersections, and
- time spent in queues.

This is represented by dashed lines in (Fig. 2.8) to indicate that taxi to an active runway is not completed until the entire distance has been travelled, for illustration taxing out and take-off procedures are shown in Annex 1.
<table>
<thead>
<tr>
<th>ACTIVITY-EVENT</th>
<th>TIME SEQUENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>System entry: Top of Descent (TOD);</td>
<td>Airspace</td>
</tr>
<tr>
<td>Descent;</td>
<td>Airfield</td>
</tr>
<tr>
<td>TMA entry;</td>
<td></td>
</tr>
<tr>
<td>4D regulation;</td>
<td></td>
</tr>
<tr>
<td>ILS path;</td>
<td></td>
</tr>
<tr>
<td>Final approach;</td>
<td></td>
</tr>
<tr>
<td>Cross threshold;</td>
<td></td>
</tr>
<tr>
<td>Exit Runway;</td>
<td></td>
</tr>
<tr>
<td>Taxi towards stand;</td>
<td></td>
</tr>
<tr>
<td>Hold at control points;</td>
<td></td>
</tr>
<tr>
<td>Move to stand;</td>
<td></td>
</tr>
<tr>
<td>Begin gate activity.</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2-9 Arrival Activity Events Sequence.
If the pilot decides to taxi out with less than all engines, the shutdown engine must be started and operating prior to beginning the take-off check activity. It is estimated to take about 2 minutes to start the engine and complete the pre-take-off checklist prior to take-off.

The departure activity sequences illustrate the problem faced by pilots when they consider taxi in less than all engines. Their objective is to time the point at which the shutdown engine is started such that it is stabilized and the take-off checklist complete at the time they receive clearance for take-off. The difficulty lies in the uncertainty of whether or for how long they may be delayed before they receive clearance.

2.2.1 Arrival Activity Sequences
The Figure 2.9 illustrates the sequence of arrival activities. This activity begins when an aircraft exits from the runway. Engines can be shut-down for less than all engine taxi approximately one and one half minutes after the taxi activity is started. APU’s, if needed, are started as the aircraft approaches the gate. Engines are shut-down and gate operations begin when the aircraft stops at the gate position.

Taxi routes for arriving aircraft connect gate locations with a number of runway exits. Runway occupancy times are decreased if exits are made at the first exit at which landing speeds have been reduced enough to permit a safe exit. Since runways must be long enough for an aircraft to be able to stop if a critical flying speed is not obtained during take-off acceleration, the distance needed to stop is not normally as long as the runway. Therefore, midfield exits are used for the typical landing.

The time needed to taxi from an active runway to a gate consists of the time needed to taxi towards the gate, the time associated with holding at control points, and any time the aircraft must wait for a gate to be released. These times are shown as dashed lines in Fig. 2.9 to indicate that the taxi activity is not completed until the entire distance has been travelled.
CHAPTER THREE

COMMUNICATION AND CONTROL

3.1 Introduction
In this chapter a survey is given of the communication and control aids used for the guidance of aircraft during their ground operations. This analysis extends to the near airspace environment since path control and guidance must be achieved continuously from airborne trajectories to ground movements and from ground movements to airborne trajectories. First the organization of the air terminal area is briefly described.

3.2 The Airspace Environment
In the terminal airspace, where large numbers of aircraft are operating in a limited area particularly with climbing or descending manoeuvres, it is customary to provide external assistance, in the form of active air traffic control, in order to get positive separation between individual aircraft. Since it is undesirable to have a mixture of controlled and uncontrolled traffic in the same airspace, the means adopted to exclude all traffic which is not subject to control has been to promulgate a rule that regulated airspace can only be entered by aircraft which have a communication link with the appropriate air traffic service unit. The most common parts of regulated airspace are: Airways, Control Zones (CTZs) and Terminal Control Areas (TMAs).

3.2.1 Airways
Airways are set up to connect the main areas of population within a particular geographical area and to link up with the major cities of adjacent regions. They are usually a minimum of 10 nm wide and generally have a variable base between 3000 feet and flight level 55, and with some exceptions extend vertically up to flight level 245, the base of the upper airspace. Their purpose is to protect the flight paths of aircraft which are flying en-route between destinations served by the airways network, or to a specified point of departure from the system.
3.2.2 Control Zones.
At busy aerodromes CTZs are established, usually within a terminal area complex, and they extend upwards from ground level to 2500 ft or a level appropriate to the base of the surrounding terminal area. Their purpose is to protect the flight paths of aircraft arriving or departing from it.

3.2.3 Terminal Areas.
TMAs are established around one or more busy aerodromes and extend usually from 2500 feet or the top of the concerned control zone to a height of approximately flight level 245 (the base of the upper airspace which can vary from country to country) and the area extends laterally to connect with the system of airways serving the terminal area complex. Their purpose is to protect the flight paths of aircraft leaving the airways system to land at an aerodrome in the terminal, or alternatively the flight paths of aircraft departing the terminal, for an en-route airway. Their vertical extent is to enable protection to be given to the flight paths of aircraft which may be overflying the terminal to other destinations served by the internal or international airways system. For illustration see Figure 3.1.

3.3 Navigation and Communication Aids
The navigation aids are required not only to enable the pilot to determine his position in relation to the earth’s surface, but also to delineate the route, airways and airspaces within which air traffic services are provided, and finally to enable him to align his aircraft with the runway in use, and effect a landing at the aerodrome of destination.

Navigational aids have been increasingly needed with the growth of air traffic activity in order to reduce to a minimum the navigational error in horizontal or vertical separation. When the traffic densities are low, less navigational aids are needed and the degree of sophistication required is generally quite low. However, as air traffic congestion continues to grow, more and highly reliable navigational aids are needed to allow all-weather operation in a safe way.
Navigational aids come within two broad definitions:

**ground-based** which, as their name implies, are installations on the earth’s surface whose geographical position is known and published, and

- **airborne**, which relates to the equipment carried in an aircraft, which enables the pilot to interrogate and obtain information from the ground-based installations.

There is a third category, called:

- **on-board** navigation systems, which enables the aircraft to be navigated without recourse to ground-based aids, such as satellite navigation and inertial navigation (INS).

Radar could also be generally regarded as an aid to navigation, and, of course, it is widely used in modern air transport and military aircraft in a variety of airborne roles.

Additional facilities are, however, required for both pilots and controllers to enable them to carry out their allotted tracks, and in general terms these are known as **communication aids**. They embrace radio telephony for communication between the air and the ground, telephone networks for rapid communication between controllers and for use as data links, and teleprinter networks for the passing of routine messages and the latest of these communications devices, secondary surveillance radar (SSR), which is to be used as a data link between the aircraft and the ground, without the need to use a radio telephony speech circuit. Computers are also becoming increasingly used as a rapid method of communication. Also whilst the basic requirements for navigation and communication will remain fundamental to any system, it is undoubtedly, particularly in the field of avionics, could well outdated the methods by which these standards are achieved today.

### 3.3.1 VOR/DME

The use of navigational aids for this purpose has progressed from the radio range and its associated fan markers supplemented by non-directional beacons, to the present-day VHF omnidirectional range (VOR) which operates in conjunction with distance measuring equipment (DME). This latter equipment enables the pilot of an aircraft to determine how far away he is from the geographical position of a VOR and a specific radial of that
facility. The VOR itself has for some 30 years been the ICAO international short-range navigational aid, and consists of a ground beacon which transmits a signal from which an airborne receiver can determine the aircraft's bearing from the beacon. It thus provides a simple means of flying radial paths either from or towards the ground station. More recently the use of airborne navigation computers combined with VOR and DME, enables the aircraft to fly desired paths, other than the direct radials, thus providing an area navigation capability.

### 3.3.2 Doppler VOR (DVOR)

DVOR, so called since the well-known Doppler principle is used in generating the ground beacon signals, has considerably improved the VOR system performance since such beacons have much greater immunity from multipath propagation effects.

Multipath effects describe a situation where both direct and indirect signals occur, causing noticeable variations in course indications. Large built-up areas close to the beacon, or mountainous terrain between the beacon and aircraft, are sources of this particular problem, largely overcome by DVOR. These navigational aids, are physically located on the earth’s surface and aircraft using their radiated signals will eventually arrive at the same spot on the earth’s surface. An exception to this is the equipment (DME) which together with VOR, permits an aircraft to be navigated, if desirable, using its on-board computers, on a course parallel to the physical position of the associated ground aid.

Closer to the environment of the airport, navigational aids of the types previously described play a vital role in the efficient operation of the terminal area surrounding the airport complex.

### 3.3.3 Precision Approach Radar (PAR)

This is an equipment located on the ground adjacent to the runway and is independent of airborne navigation equipment. These facilities may be used as a primary landing aid or, as frequently, in conjunction with ILS. The PAR radarscope gives the controller a picture of the descending aircraft in azimuth, distance, and elevation, permitting an accurate determination of the aircraft's alignment relative to the runway centreline and the glide slope.
Therefore, this equipment can be used only on the final approach area, where corrections to the approach are given to the pilot by voice communication from the monitoring air traffic controller.

### 3.3.4 Airport Surveillance Radar (ASR)

This equipment gives information to the airport tower operators about their terminal area traffic control and aircraft location. It is a two-dimensional aid and does not give information on aircraft altitude. Surveillance radar presents target information on radar displays in the control tower or the air traffic control centre. The equipment is used in conjunction with other navigational aids for instrument approaches.

### 3.3.5 Airport Surface Detection Equipment (ASDE)

These radar systems are specially designed for use at large, high density airports to aid controllers in the safe maneuvering of taxiing aircraft that may be difficult to see and identify because of airport configuration, aircraft size, or poor visibility conditions.

### 3.3.6 Instrument Landing System (ILS)

A ILS is an approach and landing aid, defining an approach path (runway alignment and glide slope) from the signals radiated by two ground transmitters. A two needle instrument indicates to the pilot in the cockpit the relative position (horizontal and vertical) of the aircraft in relation to the approach path. Thus the pilot is able to navigate in both azimuth and elevation to a point at which he can commit the aircraft to an approach to land. This aid to landing is subject to many variables and can be categorised in relation to its accuracy and integrity up to certain limits from the threshold of the runway and along the runway.

### 3.3.7 Microwave Landing System

The ILS has a number of problems which have made the development of more sophisticated landing systems necessary. The ILS is based on signals reflecting from the surface of the ground. Thus the area adjacent to the antennas must be relatively smooth and kept clear of any obstructions, such as buildings and taxiing aircraft; otherwise, the beams are distorted. There have been improvements in the transmission of the localizer beam by the installation of a waveguide antenna which confines the beam spray and
reduces the probability of reflections from buildings and other obstructions; but this has not solved all the problems associated with the ILS. The ILS provides only one path in space, which all aircraft must follow if they are using the system. Finally, there are only a limited number of frequency channels available for the ILS, and as the number of installations has increased, it is becoming difficult to provide the necessary discrete channels required.

To overcome these limitations, a system has been developed which is referred to as the MLS. Instead of providing only one glide slope as the ILS does, the MLS provides a number of slopes. In the horizontal plane, the MLS provides for any desired routes as long as they are within an area that is from 20 to 60° each side of the runway centreline, whereas the ILS provides for only one route to the runway.

The MLS is far less susceptible to interference from surrounding objects than the ILS. With the MLS, a pilot can choose any desired route to the runway at any glide slope within the vertical coverage of the system. Comparative diagrams ILS - MLS are shown schematically in Figure 3.2.

3.4 Air Traffic Control within Terminal Airspace *.

The term air traffic control service is defined as a service provided for the purpose of: Preventing collisions between aircraft, and on the manoeuvring area between aircraft and obstructions; and expediting and maintaining an orderly flow of air traffic.

At some large airports ATC is responsible for the safe separation between aircraft.

- Arriving aircraft require speed control and radar vectoring to achieve the maximum arrival rate consistent with the separation minima;

MISSED APPROACH MARKER
GLIDEPATH INTERCEPT POINT
EXTENDED RUNWAY CENTRELINE

(n.m. = nautical miles)

APPROACH GUIDANCE AREA
80° WIDE 15° DEEP

MISSED APPROACH & TAKE-OFF
GUIDANCE 40° WIDE

RANGE 20 n.m.
(30 n.m. preferred)

20 000 ft
15°

5000 ft

Figure 3-2 Comparative diagram ILS - MLS.
- Departing aircraft require minimum separations that depend on factors such as the relative speed of aircraft, the angle between departure tracks and their point of divergence, and vortex wake.

### 3.4.1 Instrument Flight Rules Overview

To channel the flow of air traffic and to obtain the necessary degree of orderliness to apply separation standards between aircraft it is essential to establish a system of airspace sufficient to protect an aircraft's flight path from take-off to touch-down, and then to apply rules regarding the use of this airspace which is designed to provide for the safety of all those who fly within it.

The rules of the air cover many aspects of an aircraft’s flight, but from the point of view of the air traffic control service the most important is the rule requiring an air traffic control 'clearance' to be obtained prior to operating a controlled flight. In another word, this means that no aircraft is allowed to enter controlled airspace without having been given a clearance to do it by the air traffic control authority responsible for that airspace.

### 3.4.2 Controlling Incoming Aircraft *

At TMA, when an aircraft approaches an airport, normally it is directed by a Control Centre to one of the reporting points located by radio beacons. These reporting points are located at specified distances along radials emanating from VHF omnidirectional (VOR) radio beacons. At most of the major airports, there is an automatic terminal information service which provides the pilots with some important information before the aircraft land at the airport. The pilots need to know the predominant weather conditions, the runway in use and the navigational approach aids available. This information is recorded and continuously transmitted on a discrete radio frequency. It is known as the automatic terminal information service. Pilots receive this recorded information while their aircraft are approaching the beacons and before direct radio contact is established with the control tower. An analogous service is operated for departing aircraft. Some times,

(*) (For example some UK major airport.)
There is a 'rush hour' at the peak times in the air just as on the ground, and aircraft may arrive at the control points more quickly than the airport is able to accept them. As it is essential that the landing separation is maintained, they have to wait their turn to initiate an approach and are instructed to form a 'stack' by rounding at different altitudes around the reporting points.

There is an agreement between airlines (a scheduling committee) to agree in advance arrival and departure times based on the airport’s stated hourly capacity, in order to avoid wasting fuel and delaying passengers at the busiest hours, see (Appendix 2).

3.4.3 Approach Control

- Is responsible for aircraft arriving at airport. It controls them from the moment when the ATC Centre hands them over until they have been lined up to land on the runway.

Normally, when an inbound aircraft is approaching one of the external reporting points, the ATC Centre informs the Approach Controller. The approach controller then awaits the first call from the pilot following his transfer to the airport ‘approach’ frequency. When he receives this call, the Approach Controller gives the pilot an initial clearance, which may include an instruction to enter the 'stack' at the reporting point if an approach delay is expected.

The Radar Controller and the Approach Controller work closely, as a rule using the same radio frequency. The Radar Controller instructs pilots to adjust their height, speed and route to ensure an orderly stream of arriving aircraft separated from departing aircraft.]

Arriving aircraft, before final approach, are transferred to another radar controller who establishes the correct landing intervals and ensures that all aircraft are correctly separated. The spacing chosen depends on a number

(*) There are three separate radar operators at Gatwick Airport: No.1 - instructs pilots to adjust their height, speed and route; No.2 - controls landing interval; No.3 - controls departing aircraft.
of factors, in particular, the prevailing weather conditions, the types of aircraft involved and the number of aircraft awaiting departure.

Wide-bodied aircraft, because of their great size and weight, create more turbulence to the air through which they pass than smaller or slower aircraft. As this turbulence can upset the flying characteristics of lighter aircraft following behind, greater separation distances have to be provided, see (Appendix 3).

3.4.4 Aerodrome Control
At final approach, a distance of some six to eight miles from the runway threshold, when arriving aircraft are satisfactorily merged into one stream and aligned with the runway, responsibility for their control is transferred to the Air Controller in the visual control tower. It is his responsibility to ensure that the runway is safely used to its maximum capacity. At a busy single runway airport this involves continuous integration of arriving and departing aircraft.

Normally, this operates from the visual control room at the top of the control tower, where there is a panoramic view of the whole airport. Aircraft are controlled from there on their final approach to land, when they are preparing for departure, when they are taxiing and vehicles moving on the runways and taxiways are also controlled from the visual control room.

From this position it is possible to overlook the whole of the airfield, the Air Controller can see that the runway itself is clear, he then issues landing clearance to the pilot of the first incoming aircraft. He gives the current direction and strength of the surface wind, condition of the runway surface (when necessary) and, if for any reason it is not safe to land, he will issue 'missed approach' instructions.

3.5 Ground Movement Control
It is important, after each aircraft has landed, that it should leave the runway as quickly as possible. The runway must be kept clear for the next arriving aircraft which may be already in final approach. Following the clearance of the runway, the Air Controller instructs the pilot to contact
the Ground Movement Controller (GMC) who then directs the aircraft to its parking stand.

The GMC is responsible for watching the inbound taxiing aircraft’s progress, integrating its movement with other aircraft and vehicles. He also, assists in separating taxiing aircraft (both arriving and departing), aircraft being towed and airport service vehicles. All this traffic is in radio communication with the GMC.

When there is good visibility, the GMC controls aircraft and vehicles by direct observation. At night, and during low visibility conditions during the day-time, aircraft are guided by the taxiway edge and centreline lights. The Air Controller, Ground Movement Controller and Lighting Operator are assisted in monitoring the movement of aircraft and vehicles during the night and in poor visibility by a ground movement radar.

3.5.1 Controlling Departing Aircraft

After an aircraft has loaded its fuel, catering supplies, baggage and passengers, the doors are closed, and the pilot makes a radio call (VHF) to the Ground Movement Planner (GMP) for permission to start so that he will not be unduly delayed either in the air or on the ground, thus saving fuel.

Factors which have to be taken into account are:

- how many other aircraft have started up,
- whether there is any congestion along the outbound air routes, and
- the availability of time and height ’slots’ made necessary by the congestion.

When the GMP has given the pilot ’start-up’ clearance and received confirmation that he is ready to move, the Ground Movement Controller takes over. He allows the aircraft to be pushed back from its stand by a tug, advises the pilot of the runway in use and guides him to the runway holding point via the taxiway system.
In general the radio channel (radio telephony) used during taxiway control operations is a common communication link to many manoeuvring aircraft and can become congested very easily. To avoid this, different radio channels should be in operation simultaneously, thus increasing the saturation of an often already overcrowded airport radio environment. With the advance of Mode S, digital communication between the manoeuvring aircraft and the tower (either a digitalized controller voice or in the future a fully automated ground control system) will allow the increase of the capacity of a common communication channel and will relieve this saturation problem.

When an aircraft approaches the holding point on the taxiway, responsibility is transferred to the Air Controller who, after consultation with Approach Control, lines up the aircraft in departure sequence to obtain the maximum use of the runway concerned.

In deciding the most suitable order for departure, the Air Controller has to consider a number of factors about the aircraft, such as: the type, the speed, the route and any departure 'slot' time or departure restriction allocated.

For example, when two aircraft of a similar type are departing in rapid succession, and the following aircraft is on a route 45 degree or more different from the landing aircraft, it might be allowed to leave one minute apart. Where aircraft follow the same route or where a faster aircraft has to follow a slower one, the time interval between successive departures has to be increased. In addition to these considerations, as with arriving aircraft, it is necessary to take into account the turbulence caused by large, heavy aircraft on departure. Minimum departure separations are decided according to the combination of aircraft involved see (Annex 3).

After becoming airborne, control of the departing aircraft is transferred to the Air Traffic Control Centre (ATCC) for integration with other en-route traffic, or to the radar controller if the initial route conflicts with arriving traffic.
3.5.2 Ground Guidance Systems

According to ICAO rules (Surface Movement Guidance and Control Systems-SMGCS, Circular 148-AN/97 and DOC 9476-AN/927) a taxi control system must fulfill the following requirements to be used under Runway Visual Range (RVR) down to 50 meters:

- A localization component which allows pilots and controllers to know the exact position of the aircraft on the airfield at any time between push-back and runway holding point or between runway exit and stand.

- A directional component which tells pilots and controllers the actual aircraft taxiing direction.

- An identification component which allows controllers to identify the aircraft by its flight number, its position and its direction.

After all-weather flight operations have been introduced step by step from the early sixties on, some aircraft have been certified to land down to an RVR of 75 meters and taxiing has become the limiting factor for low-visibility operations. However, the requirements for an all-weather taxiing system cannot be met with present day technology because optical systems alone are no longer sufficient. It seems important that new on-board guidance systems should be integrated into the general air traffic procedures.

The current method for guiding an aircraft to or from its parking position is based on the following system components:

- Centerline lighting from the runway to the apron by means of lights at the most fifteen meters apart. With this separation, the pilot can see at least three lights when the visibility is about seventy meters, so a definite direction is available.

- Stop bars may protect the runway from unintentional entries from adjacent or crossing runways. These stops bars are exclusively switched from the tower.

- Clearance bars provide the required information for a safe crossing of critical intersections.
3.6 Future Control Processes and Systems.

3.6.1 Time-based Guidance for Air Traffic Control.

At present, the decision-making process of air traffic control (ATC) in the extended terminal area (from 150 nm from touchdown) is manual. Controllers expertly direct traffic flow to maximize capacity without compromising safety by issuing to each aircraft clearances which specify speed, altitude, or heading requirements. In terms of arrivals to a single runway at a major terminal area, this is generally accomplished by spacing traffic uniformly: along each of the three to four major arrival directions; the traffic flows from the various arrival directions are uncoordinated. It is the responsibility of the final controller to take these uncoordinated flows and establish a sequence of traffic which does not violate separation constraints between consecutive aircraft.

Advances in the technologies of surveillance, digital communications, aircraft automatic flight control systems, and computer displays, networks, and software now provide the possibility of introducing real-time interactive automated decision support systems for ATC controllers. These support systems have the potential to increase the capacity and efficiency of terminal area ATC procedures.

The goals of these studies have been to increase landing rate and to reduce fuel consumption, and in addition, to reduce controller workload. Time scheduling is to be accomplished by developing a time plan, and a means of controlling aircraft to achieve a desired time, so that traffic flows which reach the final controller are coordinated, and that little maneuvering is required to achieve the final sequencing.
The key element in the time-based system is a four-dimensional (4D) algorithm which, given the present position, route, and touchdown time, generates a time table of commands to control the aircraft to follow the route specified and touchdown at the specified time.

For a number of years NASA has designed and flight-tested research systems incorporating various types of time-control methods for both Stol and conventional aircraft. These tests have demonstrated the ability to predict and control arrival time accurately under varied operational conditions, achieving arrival time accuracies of ±10 sec.

Onboard guidance systems that can predict and control the touchdown time of an aircraft to an accuracy of a few seconds throughout the descent have been proposed as an element of a future air traffic control ATC system. A crucial problem in the application of 4D guidance is the development of ATC procedures which can exploit the onboard time-control capability. The use of a time-based scheduling system in the terminal area when all aircraft are 4-D equipped and unequipped was investigated in an earlier real-time simulation study.

Path generation involves determining a complete 4-D arrival path which is feasible in terms of airspeed, climb/descent speed, etc, and which is free of conflicts from all other existing planned terminal area flight paths. It cannot be done onboard each aircraft. Because of the need to be conflict-free, it is necessarily a centralized, ground-based process. Since the schedule and the associated set of conflict-free paths are dynamically changing, it will not be efficient to commit to a fixed 4-D path early in the descent phase of aircraft arriving for landing, and landing arrival paths must be generated in a manner to allow flexibility in rescheduling. At some point closer to landing, the schedule and paths may become fixed and at that time a complete 4-D path could be transmitted to predetermine a 4-D path for


landing arrivals from top of descent (TOD) points because the landing and take-off schedule cannot be determined at that time. Take-offs have not yet entered the scheduling.

The development of effective 4-D guidance systems should have an essential influence on the organisation and scheduling of ground operations since they provide a prediction of available gaps for departing aircraft and of touch down times for arriving aircraft. Thus these flows can be better managed or optimized through scheduling processes so that waiting times, fuel consumption and pollution levels can be minimized.

Naturally it must be accepted that longer the prediction horizon and better the accuracy of the predicted times and intervals, the larger will be the possibility of an efficient scheduling of ground operation.

3.6.2 New technologies and procedures for ground guidance

Today ground guidance systems can be improved and complemented rather easily. For instance, some airports use induction loops to make the stop bars safer: a first loop informs the tower that an aircraft is taxiing from or towards the runway and as soon as an aircraft is cleared from a stop bar and has crossed it, a second induction loop detects it and switches the stop bar back to red. When an aircraft passes a stop bar without permission an alarm is triggered in the tower and the controller must intervene.

Another possibility to make taxiing safer is the subdivision of the taxiway lighting into block circuits in which only one aircraft can be present at a time, however this procedure tends to diminish the capacity of the taxiway system.

New improvements can be foreseen for the ground radar systems particularly in displaying a better image of apron and taxiways.

The all-weather taxi guidance system of the near future must be largely compatible with all-weather landing systems and offer the same degree of reliability with regard to capacity and punctuality as the present all-weather landing systems. Now with Electronic Flight Information Systems (EFIS) technology, it is easy to present on an electronic display (the Navigation
Table 3-1  Taxi guidance.
Display for instance operated under a "need to know" policy) an image of the taxiways and other traffic areas of a given airport, retrieved from the data base of the Flight Management System (FMS) of the aircraft. Then the superimposed aircraft position should give pilots a rough orientation, backed up by the optical aids available along the runways and taxiways, to find either the parking position or the entrance to the taxiway or runway system. Also, on the same display, directions could be given.

With the use of mode S, address selection and data link offer the possibility of target identification as well as aircraft position determination. The data link also allows the exchange of position and direction information so that both the tower and the pilots have a complete view of the total traffic situation.

Another good possibility which can be used in the near future for taxiing control, guidance and monitoring is the Global Positioning System (GPS), a satellite-based navigation system which has been developed for global and regional position finding and navigation. The possibility to carry out three-dimensional position finding on the ground and in the air with precise time and speed information makes this system suitable for taxiway guidance and control (see Table 3.1).
CHAPTER FOUR

Airfield Capacity.

4.1 Introduction
In this chapter the ability of an airfield to deliver acceptable levels of service with respect to aircraft ground activities is considered.

The airfield capacity concept is introduced here since it is believed that its level of saturation is an important indicator for the choice of scheduling policies either for arriving or for departing aircraft. Thus the influence of operation rules and restrictions over airfield capacity are considered.

For many decades very important efforts have been expended in the analysis of airport capacity with special attention to runways, leading to the writing of various capacity manuals.

4.1.1 General definition
The term "capacity" refers to the ability of a component of a system to accommodate units of demand. Here it is expressed in number of operations (i.e., arrivals, departures aircraft) per unit of time, typically in operations per hour.*

Different definitions have been used in airport capacity analysis. These definitions derive from two capacity concepts:

- "Ultimate Capacity", is the maximum number of aircraft that can be handled by a facility during a specified time period with constant level of demand. It is calculated as the reciprocal of the weighted average service time of the aircraft using the facility, and

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** Kanafani, 1983.
• "Practical Capacity", is defined as the number of aircraft operations that can be handled by a facility during a specified period of time such that the average delay to all processed aircraft equals a certain specified amount.

An important difference in these two measures of capacity is that one is defined in terms of delay and the other is not. *

Capacity and demand should not be confused. Capacity is concerned with the physical capability of an airfield and its components. It is a measure of supply, and is independent of both the amount and fluctuation of demand and the amount of delay imposed to aircraft **. But, Delay is dependent not only on capacity but also on the amount and fluctuation of demand. Aircraft delay can be reduced by increasing capacity and by providing a more uniform pattern of demand (i.e., by smoothing the peaks periods of demand), see Figure 4.1, where we see that as demand approaches capacity, delay for aircraft, increases sharply.

There are many factors that influence the capacity of an airfield, and some are more significant than others. In general, capacity depends on the configuration of the airfield, the environment in which aircraft operate, and the availability of aids to navigation and air traffic control facilities. A listing of the most important factors embrace:

• The traffic mix of aircraft using the facilities.
• The pressure factor (effect of workload on controller / pilot efficiency); Pilot / controller skills: training, experience, attitude.
• The ATC procedures: rules, regulations and letters of agreement.
• The weather, particularly visibility and ceiling, since air traffic rules are different in good weather than in bad weather.

* Prediction of DELAY is the key to understanding Economic Penalties; Queue Sizes (congestion on taxiway and Stacks); requirements in Gates and Stands, Controller Workload.

Figure 4.1 Relationship between delay and capacity
• Ratio: the number of arrivals relative to the number of departures.
• The runway occupancy time for arriving and departing aircraft.
• Turbulence: the existence and frequency of occurrence of wake vortices which require greater separations when a light aircraft follows a heavy aircraft than when a heavy aircraft follows a light one.
• The availability and structure of airspace for establishing arrival and departures.
• The nature and extent of the air traffic control facilities (Navaids / approach aids / landing aids).
• Within the constraints of wind and noise abatement, the strategy which the controllers choose to operate the runway system.

The airport capacity can be broken down following the main components of the airfield.

4.2 Airfield Capacity and Delay

For determining airport capacity and delay, the operations on the runway, taxiway, and gates at most airports can be considered independent of each other and analyzed separately since generally the capacity of one component does not affect the capacity of another. Then the capacity of the entire airfield is governed by the capacity of the component which is the more restrictive. In the same way since operations on one component have little influence on the delay suffered by aircraft on another component, the total delay for aircraft on the entire airfield can be estimated by adding the delay of each aircraft over each individual airfield component.

• Gate Capacity,
• Taxiway Capacity,
• Runway Capacity.
4.2.1 Gate Capacity.
The word gate indicates an aircraft parking space, adjacent to a terminal building and used by a single aircraft for the loading and unloading of passengers, baggage, and mail.

Gate capacity can be defined as the maximum number of aircraft that a fixed number of gates can accommodate during a specified interval of time when there is a continuous demand for service.

The items that affect gate capacity are as follows:

- The number and type of gates available to aircraft,
- The mix of aircraft demanding apron gates and gate-occupancy time for various aircraft,
- The efficiency of apron personnel,
- Restrictions in the use of any or all gates.

4.2.2 Taxiway Capacity.
Some empirical studies have indicated that capacity of a taxiway system normally far exceeds the capacities of either the runways or gates. In order to achieve a taxiway capacity improvement, some basic points should be stressed:

- Providing full-length parallel taxiway to minimize the need for backtracking on a runway.
- Providing independent taxi routes for departing and arriving traffic.
- Minimizing runway crossing times by providing direct crossings, as well as multiple crossing points so that two or more aircraft can cross an active runway simultaneously.
- Placing the departure runway closest to the loading apron so that departing aircraft do not have to cross the landing runway.

Because taxiway systems include runway entries and exits, some additional points should be considered.
Normally, departures flying the same route will require more separation enroute than the amount of separation required between successive take-offs by other flights from the same runway. In many cases, it is necessary for air traffic control ATC to withhold the take-off clearance of one aircraft until adequate separation has been established behind a preceding aircraft on the same route. In these cases, it would be desirable if the control tower could resequence the departures so that other aircraft going out on other routes could take off ahead of the aircraft being delayed.

If the taxiway resembles Figure 4.2(a), however, there is no convenient way to change the take-off sequence. If the first aircraft is delayed for any reason, it blocks all the aircraft behind it. The result is an irretrievable loss of capacity.

This situation can be avoided by providing a by-pass area such as that shown in Figure 4.2(b). In this case, a delayed departure need not block the flow of other departures. An even more advanced solution is the runway entry shown in Figure 4.2(c). With this configuration, either aircraft could be cleared for a rolling take-off independently of the others. The ability to use a rolling take-off could reduce the interval between a take-off and a landing by approximately 15 seconds.

4.2.3 Runway Capacity.

Runway capacity is normally the controlling element of the airport system capacity, and is determined by three groups of interrelated factors:

- Airport and Route configuration/facility,
- ATC methods of Operation, and
- Traffic Mix.

A) Airport and Air Route Configuration/Facilities.

These include the number and relative positions of runways, which determine the possible modes in which the airport can operate; the size and positions of departure holding points and runway exit taxiways, which affect the flow of aircraft; and the separation between aircraft in the air which depend on the use of radar, appropriate air route configurations and the need to take account of the vortex wake from aircraft (i.e., In order to
Figure 4.2 Taxiway and runway entry.
Figure 4.3  Time-distance diagram for two approaching and one departing aircraft: open box, runway occupied by departure; black box, runway occupied by arrival.
increase capacity, departures can be inserted between pairs of arrivals, as illustrated by Figure 4.3).

B) ATC Methods of Operation.
Instrument Flight Rules (IFR) operated by Air Traffic Control are responsible for the safe separation between aircraft. Arriving aircraft require speed control and radar vectoring to achieve the maximum arrival rate consistent with the separation minima and on factors such as the relative speed of aircraft, the angle between departure tracks, the point of divergence and vortex wake.

C) Traffic Mix and Separations.
Arriving and departing traffic usually include aircraft of different sizes which require "vortex wake separation minima" between them. As an example, a 'Small' aircraft on final approach is required to be at least 6 nautical miles behind a previous 'Heavy' aircraft. In the extreme, where a very small aircraft trails a heavy aircraft, the UK requires a separation of 8 nautical miles, see Appendix 3. At an airport where arrivals and departures use the same runway, the proportions of arriving and departing flights also influences capacity. The capacity tends to be reduced if the proportion of arrivals in the total movements is markedly greater than 50%, because of the increased difficulty in achieving the optimum interleaving of departures into the arrival stream, as shown in (Figure 4.4).

4.3 Operation Rules and Occupancy Times at the Runway

4.3.1 Arrivals and Departure Rules
Various strategies are available for traffic controllers to manoeuvre aircraft, but there are certain rules, which must be obeyed.

- (1) Arrivals have priority over departures.
- (2) For any aircraft, which is moving during landing or take-off, the runway ahead of it must be free of other aircraft.

"Arrivals have priority over departures. It is not entirely clear what this means. Some people have interpreted it to mean that an arriving aircraft which is at least 3 N.m. from another (light) arriving aircraft is allowed to land with no delay; and if there is a queue of arriving aircraft, the
Figure 4.4 Achieving the optimum interleaving of departure into the arrival stream.
controller is obliged to land the aircraft at the maximum possible rate. "In fact, no one forces the controller to land aircraft with the minimum spacing; he can pretend to be very cautious and use 4 n.m. separations, then squeeze in a departure. If the rate of expected arrivals is too high, the controller can also order a pilot to waste time far from the airport or even not take off from his origin airport until some specified time. It is common practice now for a pilot to be assigned a landing time long before he reaches the airport. If there is a large queue for departures, the controller can ask the approach control to hold up the arrivals completely. Obviously, landing aircraft have "priority" over departures, once they have entered the final approach. A controller will not "wave off" a landing except in an emergency, but nothing prevents the controller from scheduling the times the aircraft enter the final approach. Thus, the "priority rule" seems, in practice, to be redundant or meaningless".*

A traffic controller or pilot must, therefore, do nothing at any instant, which will force a violation of this rule to occur at any later time despite unpredictable events. Since it is not possible to stop an arrival or departure already in progress, it must always be possible to wave off an approaching aircraft even if a departure or arrival aircraft on the runway should have an accident.

A direct application of this rule determines the minimum time between an arrival and a departure (A-D). A departing aircraft cannot be released for take-off before the arriving aircraft has exited. A departing aircraft turns onto the runway almost from a hold point (a pilot cannot anticipate the exit time of the arrival and take a running start from the taxiway) but a clearance to depart can be communicated with very little loss of time when the arriving aircraft has been observed to have left the runway.

The above rule also regulates the minimum time between two departures (D-D). If one aircraft departs behind another, it must wait at least until the leading aircraft lifts off. If the second aircraft will follow a path to the same departure fix, it should also maintain a 3-mile spacing (or more) in the air. If the aircraft go to different departure fixes, consecutive departures on the

same runway are usually spaced at a minimum of one minute (except for departures after a heavy jet).

The minimum spacing between two successive departures is determined by reference to either the wake vortex spacing minima Appendix 3 or the departure track criteria, which are shown at Table 4.1.

All the pairs of departure tracks are examined to see whether they diverge by more than 45 degrees. For those diverging by more than 45 degrees, a one minute separation is assigned to the value of taxi time. For those diverging by less than 45 degrees, if the first aircraft is from the heavy or medium weight category and the second is small or light, then the separation is two minutes, but for all other combinations it is taken as five minutes. This assumes that heavy and medium aircraft have high departure speeds compared with small and light aircraft i.e. a smaller separation can be applied since the second departure will always be increasing its separation after take-off due to its lower speed. This assumption is generally valid since most heavy / medium aircraft are jet powered and have a substantially higher climb-out speed than do the mainly turboprop or piston-powered small / light aircraft.

Under visual flight rules, this single occupancy rule is essentially the only rule that applies; the pilots are mainly responsible to see that it is obeyed. Under IFR, however, it is necessary to formalize the mechanism by which the rule is obeyed by imposing further rules which are easier to follow or enforce.

Since a controller does not wish to wave off an arrival except in an emergency, there is another rule.

• (3) A departure cannot be released if an arriving aircraft is within some distance $D_d$ of the runway (presently 2 nautical miles). Equivalently, a departure must be allowed about 1 min to get off the runway.

This, in fact, does not give much time to spare; but since the arriving and departing aircraft would be at opposite ends of the runway, if they failed the rule, there is not much danger. In an emergency, the arriving aircraft could "touch and go"(depart after it had already touched down).
<table>
<thead>
<tr>
<th>Minimum Separation</th>
<th>Provisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 min.</td>
<td>Aircraft must fly on tracks diverging by 45 degrees or more immediately after take-off (may be reduced if aircraft are taking off from independent diverging or parallel runways)</td>
</tr>
</tbody>
</table>
| 2 min.             | (i) Preceding has filed a TAS of 40 knots or more faster than the following  

(ii) Neither aircraft is cleared to execute any manoeuvre that would decrease the 2 min. separation between them. |
| 5 min.             | Preceding aircraft has TAS > 20 knots or more faster than the following  

Providing that the 5 min. separation is maintained up to a reporting point, within or adjacent to a control zone or terminal control area, and the aircraft will subsequently be separated either  

- (i) vertically  

- (ii) by tracks which diverge by 30° or more, or  

- (iii) by radar |
| 5 min.             | No provisions |
| 10 min.            | Ref. "The Manual of ATC" by the CAA |
At the final approach the pilot does not know exactly when an arriving aircraft ahead of him will turn off the runway; when he does know, he can no longer adjust his arriving time. There must be some safe following distance, which will guarantee that (Rule 1) is satisfied. Also, care must be exercised to avoid collisions along the approach path itself.

- (4) Two arrival aircraft (A-A) must maintain at least a certain minimum spacing $D_{AA}$ when on the same flight path (particularly at the final approach).

This minimum distance was chosen to be 3 n.m. until the heavy jets were introduced. It should apply at all points along the approach path. If a slower aircraft is following a faster one, the rule, in effect, applies only at the final approach, i.e., the second aircraft must be a distance $D_{AA}$ from the approach gate when the first aircraft reaches the approach gate. This spacing will, of course, increase as the aircraft traverse the final approach path. If, on the other hand, a fast aircraft is following a slower one, the critical point where the rule applies is at the threshold. At the approach gate the spacing must be larger than $D_{AA}$ to compensate for the speed difference.

- (5) Heavy jets generate considerable wake turbulence, which may be dangerous to an other aircraft type following too closely.

Although for consecutive departures the above rules imply a minimum time separation of about 1 min, if the leading aircraft is a heavy jet this time separation is increased, see Appendix 3.

4.3.2 Occupancy Times

Runway Occupancy Time (ROT) by landing aircraft is one of several elements which collectively comprise airfield capacity. As ROT is reduced, airfield capacity is proportionally increased until arrival or departure separation become critical. Thus, the air transportation system can accommodate increased traffic and help reduce costly delays, as well as accommodate future traffic increases. The key to achieving reduced ROT is to provide runway exit taxiways located and designed to give the pilot visual
queuing for safe runway exiting at higher than normal speed (between 30 and 60 knots.)

A) Arrival Runway Occupancy

Various studies concerning runway occupancy have produced similar results. In 1978, Koenig analyzed observations collected; in 1979, Jackson and Moy verified Koenig's results. In 1990, Ruhl have done a empirical analysis of runway occupancy with applications to exit taxiway location and automated exit guidance", with an improved knowledge of the aircraft arrival process.

The arrival service rate of a runway is defined as the average number of arrivals landing per. hour when there is a continuous queue of demanding aircraft for landing. This service rate is determined primarily by:

- The traffic mix, in particular the proportion of "heavy" aircraft.
- The achieved separations between successive pairs of arrivals.

The achieved separations will depend upon conditions at the time. For example, a wet runway could lead to an increase in runway occupancy, since the deceleration time required will be greater than that for dry conditions, and so there will be a need for additional time spacing on approach.

On approach, the most vital consideration is the accurate achievement of the correct conditions at the threshold (ie. height, speed, descent rate, track and power). To achieve these conditions consistently, the ground aids must be satisfactory and the aircraft must have adequate performance on the approach to correct discrepancies in the flight path and to respond to emergencies. Speed control is harder for modern jet aircraft in comparison with older slower types, because the minimum drag speed is higher relative to the stall speed, and so the aircraft can arrive at a condition of zero speed stability.

The runway occupancy time of an arriving aircraft is the time taken between crossing the threshold of the runway, and clearing the runway after landing. This time depends on a number of factors, such as:

- Approach speed of aircraft and differences in approach speeds,
- Wake turbulence,
- Taxi speed of aircraft,
- Height of flare initiation,
- Screen height,
- Number and Position of runway turn-offs,
- Maximum allowable speed for each turn-off type,
- Deceleration of aircraft,
- The circumstances: load factor (approach speeds), wind and wind shear;
- The accuracy of facilities available to the controller to monitor approaches and enable him to identify and avoid closing risks: precision of vectoring up to the ILS gate, number of aircraft handled by the controller, communications traffic.

After touchdown an aircraft can clear the runway in one of two ways:

- If the speed of the aircraft when next to a turn-off is less than the maximum safe speed for that turn-off, then it is possible to clear at that point.
- If the aircraft has slowed to its taxi speed before reaching a turn-off, it should continue at this taxi speed until the turn-off is encountered.

B) Departure Runway Occupancy

The departure occupancy time is the sum of the times to accomplish the two departure manoeuvres on the runway:
The first, "Line-up manoeuvre", is defined as the time from the ATC clearance (to leave the holding point for line-up), to completion of line-up on the runway.

The second "take-off manoeuvre", is defined as the time from when the aircraft is cleared to roll by ATC to the time that the wheels leave the runway (airborne). If take-off is taken "on the roll" then the initial time is taken as the time the aircraft is lined-up.

Generally, no aircraft moves onto the runway before the preceding aircraft has taken off, the minimum longitudinal separation is respected as long as the two aircraft are on the same path.

ATC delays often necessitate the issuing of departure "slot times" to departing aircraft which are due to fly through airspace in which the delays are occurring. This time, which is usually given as 3 mins., is normally the time by which the aircraft must be airborne, although occasionally a time is quoted by which the aircraft must have reached a specified waypoint.

A missed slot can result in long delays on some routes, and so the ATC Officer will always try to ensure that slot times are achieved. The presence of restricted aircraft when there is a queue at the holding point of the runway will affect the departure sequence of individual aircraft. Sometimes a slot allocated aircraft will be overtaken by others as it waits for the beginning of its slot time, at other times it may go to the head of the queue if deadline is fast approaching. However, aircraft will usually arrive at the holding point before their slot times in order to be sure of making them, and so have to wait for a finite period of time before they can be considered for departure.

Although individual aircraft might suffer additional delay because another aircraft is on a slot, the average delay is not necessarily increased; this would only happen if the runway was not utilised as much. The reason why restricted aircraft have such a small impact on runway capacity is that any potential problems are to a large extent anticipated and resolved by ATC before they occur. For example, slot times might be altered if a number of aircraft have the same slot. Slots are fairly frequently altered in practice, in
order to allow aircraft to go either earlier if they are ready, or later if there is a long queue at the hold.

If more aircraft were to be restricted than is usual at most airports, controller workload would increase, and thus flexibility may then not be possible, leading to a possible reduction in runway capacity.

C) Occupancy Times with Mixed Operation

An outbound aircraft cannot move onto a runway unless it is clear and an approaching aircraft is over two nautical miles (sometimes 3 minutes) from the threshold.

The Figure 4.4* shows that it may be necessary to increase the separation of arrivals at the approach the runway threshold in order to introduce a departure between two arrivals. Alternatively, runway occupancy (assumed as corresponding to 1 nautical mile on the figure) has to be reduced by opening a rapid exit enabling the runway to be freed sooner.

If departures are less frequent than arrivals, there comes a time when there is no advantage in increasing spacing between two arrivals in order to insert a possible departure which does not in fact take place. The probability of it being possible to insert a departure in the arrivals queue depends on the distribution law for intervals between arrivals and the distribution law for runway occupancy times in the case of departures.

If the sum of runway occupancy times of the landing and the take-off which follows it is equal to the interval between two arrivals, the runway may be constantly occupied and reach its maximum capacity.

When the departure queue is too long, the controller may be prevailed on to make the arrivals wait in order to enable a series of outbound aircraft, previously classified by different destinations with the aim of using the lowest possible separations, to take-off.

4.4 Other Factors Affecting Airfield Capacity

4.4.1 Wake Turbulence Separation.

It has long been known that the wake from aircraft can be sufficiently powerful to cause a disturbance to a following aircraft under certain conditions. This is especially true for light aircraft: there have been several reports of light aircraft experiencing difficulty when encountering the wake of heavier aircraft. With the development of the wide-bodied aircraft, it was realised that the wake from such aircraft might be hazardous to the following aircraft.

Until several years ago, therefore, landing aircraft maintained a three mile separation and departing aircraft intervals were only limited by controller workload, under IFR conditions. The growing concern over trailing wake vortices as a possible cause of accidents let the FAA(1970) to increase the IFR separations behind heavy jets* to four and five miles on landing, and to at least two minutes between operations on departure. United Kingdom(1974) took similar steps by increasing the separation between certain heavy jets and other aircraft to six miles.

Today the rules determining separation standards required to avoid wake turbulence are complex, but in broad terms the greater the weight difference between the turbulence-creating and the experiencing aircraft, the greater the required separation. This separation is normally defined in terms of time with respect to departing aircraft, and in terms of distance with respect to two aircraft on approach to landing on the runway. Appendix 3 shows the wake vortex spacing minima of final approach for (ICAO and UK) standards and shows the wake vortex spacing minima for departures.

For the purposes of this thesis, the UK standards of weight category were used. This was because the UK standards provide four categories as opposed to ICAO’s three, and it was felt that a better estimate of runway capacity could be obtained by making use of this more detailed definition.

* Cross take-off weight over 300 000 lb.
4.4.2 Weather conditions.
One of the prime consequences of operations in inclement weather is reduced runway capacity, due to increased runway occupancy time.

Not only will average times increase by a third as traction varies from excellent to nil, but the standard deviation of occupancy times will also increase. This is a function of the decreasing value of high speed exits as well as the increased braking distance, in that a radius of 300 metres, which would be acceptable for 50 knots in good weather, will only be useable at 20 knots in slippery conditions. On the other hand, the aiming point for touchdown is a function of the distance from the critical capacity parameter when inclement weather forces the occupancy time up 90 seconds, a case can be made for designing exit location and angles in relation to an aircraft’s poor weather landing performance.

4.4.3 Wind shear and crosswinds.
The most serious form of wind shear is associated with the cold air gust front preceding a thunderstorm. It is the horizontal shears produced by turbulence in the cold sublayer and by the reversed direction of the warm inflow moving up and over it that cause the worst problems. Many accidents have been attributed to wind shear on final approach. At airports where this phenomenon is common, there will regularly be periods when arrivals cannot be given permission to land, or when aircraft need to go around prior to landing to check for wind shear. At these times the capacity of the runway is therefore restricted.

4.4.4 Low visibility conditions.
Movements in Category III (very low visibility) conditions, which at one time were limited to occasional low visibility departures, have now become commonplace for both arrivals and departures.

At the present time it is the practice of ATC in Category III conditions to provide longitudinal separation of approximately four minutes or ten miles. With this separation the maximum landing rate of a dedicated runway is reduced to approximately 15 arrivals per. hour, compared with the normal rate of 31 or 32 per. hour.
This reduction in the sustainable capacity of the landing runway is due to a number of factors, in particularly:

The need to protect the integrity of the ILS signal against multi-path interference by mobile obstacles in the localiser sensitive area.

The time taken by the landing aircraft to clear the obstacle free zone i.e. excessive runway occupancy.

The runway occupancy problem results from the pilot's lack of knowledge of his position in relation to the exit taxiways. On completion of the landing run the pilot will inevitably taxi comparatively slowly, "feeling" his way towards and into the exit taxiway. The problem would be resolved if a method could be devised of providing the pilots with "distance to go" information to reach the first available turn-off.

The problem is not so acute in the case of departing traffic. Once the aircraft has found its way to the holding point, there is only the matter of lining up on the runway centreline which may take longer than normal in poor-visibility conditions, and at the most this would be ten seconds or so extra.

4.4.5 Noise Abatement

Noise abatement restrictions can reduce airport capacity by restrictions the hours of airport operation or the use of certain runways or routes. At some major airports with dual parallel runways simultaneous parallel approach procedures cannot be established because landings are restricted to alternate runways in specified time blocks on alternate days.

In the U.S., considerable technical progress has been made in reducing engine noise during the past few years as a result of Federal Aviation Regulation Part. 36. The current development of prop-fan technology should further reduce the noise footprint - the area on the ground affected by airport noise - at many locations.

Within this footprint, however, the total noise may gradually increase due to the continued increase in traffic demand. Zoning the footprint area for non-residential use should provide better compatibility between the airport
and its environment. The compatibility can be further enhanced through the use of perimeter tree planting or the construction of other sound barriers to reduce the noise effects of ground operations, such as engine run-ups and thrust reversals, on the surrounding neighbourhood.

4.5 Measuring the Level of Saturation of an Airfield

The level of saturation of an airfield can be estimated by comparing actual flows with the capacity of the operating runways *.

Let $\tau_{\alpha\beta}$ be the inter-event time (touch down or lift off) for an aircraft of class $\alpha$ "followed" by an aircraft of class $\beta$. Let $\rho_{\alpha\beta}$ be the probability of such an event. Then the average flow of aircraft over a unit of time is given by:

$$\lambda = \frac{1}{\sum_{\alpha\beta} \rho_{\alpha\beta} \cdot \tau_{\alpha\beta}}$$

The capacity is the maximum value of $\lambda$ obtained from a set of feasible operations strategies. This maximum $\lambda_c$ will be attained when $\tau_{\alpha\beta}$ is chosen as small as possible when $\rho_{\alpha\beta}$ is not negligible:

$$\lambda \leq \lambda_c = \frac{1}{\sum_{\alpha\beta} \rho_{\alpha\beta} \cdot \tau_{\alpha\beta}}$$ (x)

If the rate of arrivals is $\lambda_a$ and the rate of departures is $\lambda_d$, we have

$$\lambda = \lambda_a + \lambda_d$$

Expression (x) can be rewritten as:

$$\sum_{\alpha\beta} \lambda \cdot \rho_{\alpha\beta} \cdot \tau_{\alpha\beta} \leq 1$$

If it is supposed that $\lambda_a < \lambda_d$ and that each arrival is served as soon as possible but always after a departure, then:

$$\lambda \cdot \rho_{d\alpha} = \lambda \cdot \rho_{d\alpha} = \lambda_a$$

and $\lambda \cdot \rho_{d\alpha} = \lambda_d - \lambda_a$, $\rho_{a\alpha} = 0$

The capacity constraint implies:

Finally in the case where $\lambda_a > \lambda_d$ we have:

$$\lambda_d \left( \tau_{ad} + \tau_{da} \right) + \left( \lambda_a - \lambda_d \right) \tau_{da} \leq 1 \quad \text{for} \quad \lambda_d < \lambda_a.$$

These linear inequalities define a feasible region in the $(\lambda_a, \lambda_d)$ space for this strategy.

If all arriving aircraft are first served and then all departures are treated then the capacity constraint becomes:

$$\lambda_d \cdot \tau_{dd} + \lambda_a \cdot \tau_{aa} \leq 1$$

In the case where aircraft of different classes are mixed this analysis is more intricate since variable separation rules must be considered either at take off or landing.

In any case a useful measure of saturation of an airfield system will be given by the "distance" of the current $(\lambda_a, \lambda_d)$ point to the capacity boundary. Let $\varphi (\lambda_a, \lambda_d) = 0$ be the equation of the boundary, different measures of distance can be used. For instance:

$$s_1 = \frac{1}{\min_{M \in \varphi} \sqrt{(\lambda_a - \lambda_{aM})^2 + (\lambda_d - \lambda_{dM})^2}}$$

$$s_2 = \frac{1}{\min \left\{ (\lambda_a - \lambda_{ak}), (\lambda_d - \lambda_{dk}) \right\}}$$

For illustration see Figure 4.5.

Other qualitative measures of saturation may be also easily obtained.

4.6 Final Observations

The estimation of the level of saturation of an airfield is an important indicator for the choice of a scheduling policy for aircraft ground movements since it is related with two fundamental considerations:

The importance of queuing delays which should be minimized.

The accuracy of the prediction of gaps at the runways.
Figure 4.5 Rates of arrivals and departures

Capacity boundary under current strategy

\[ \varphi(\lambda_a, \lambda_d) \]
In relation to the first point, the greater the level of saturation, the greater the queuing delays and the greater the value of any savings in time, fuel or pollution.

In relation to the second point, the study of queuing processes through the Theory of Stochastic Processes shows that as the level of saturation of a servicing system rises, the variability of service time increases. So it must be expected that the accuracy of estimation of touch-down and take-off times will decrease with a larger level of saturation. This must have noticeable consequences on the scheduling practice for ground movements.
CHAPTER FIVE

Fuel Consumption and Pollution by Ground Operations

Ground Operations at airports are the source of important fuel consumption and pollution emissions. Their reduction are of interest not only for airlines but also for airport managers and the neighbouring community. Many studies have been already developed not only to upraise their effective amount and impact but also to try to minimize them through the use of new operations policies and equipments.

5.1 Fuel consumption by aircraft ground operations

Fuel consumption by aircraft ground operations depend on many factors such as:

- size and load of the aircraft;
- type and number of engines;
- engine running policy at ground (start up, idle regimes,...);
- distances to be covered during taxiing;
- taxi surfaces;
- delays with running engines.

Table 5.1 displays the engine designation for the main western aircraft types while table 5.2 gives the fuel flow rates (Kg/hr) for different types of engines. Fuel flow rates are shown for the engine taxi-idle (7% Full Thrust), approach (30% FT), Climbout (70% FT) and Take-off (100% FT).

Other data from Boeing Aircraft relative to fuel consumption under taxi conditions is listed in Table 5.3.

- Page 70 -
<table>
<thead>
<tr>
<th>Aircraft class</th>
<th>Representative aircraft</th>
<th>Engines per aircraft</th>
<th>Engine commonly used</th>
</tr>
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<tr>
<td>Jumbo jet</td>
<td>Boeing 747</td>
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<td>Pratt &amp; Whitney JT-9D</td>
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<td></td>
<td>Lockheed L-1011</td>
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</tr>
<tr>
<td></td>
<td>M. Douglas DC-10</td>
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<td></td>
</tr>
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<td>Long-range jet</td>
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<td></td>
<td>M. Douglas DC-8</td>
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<td>M. Douglas DC-9</td>
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<td>Electra L-188</td>
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<td>Gates LearJet</td>
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<td>General Electric CJ610</td>
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<td>-</td>
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<td>Lycoming 0-320</td>
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<td>Military piston</td>
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<td>Curtiss-Wright R-1820</td>
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Table 5.1 Aircraft Classification
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<th>Engine</th>
<th>Fuel rate (kg/hr)</th>
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<tr>
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<tr>
<td>Pratt &amp; Whitney JT-9D (Jumbo jet)</td>
<td>788</td>
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<td>General Electric CF6 (Jumbo jet)</td>
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<td>Pratt &amp; Whitney JT-3D (Long range jet)</td>
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<td>Pratt &amp; Whitney JT-3C (Long range jet)</td>
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<tr>
<td>Pratt &amp; Whitney JT-4A (Long range jet)</td>
<td>630</td>
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<tr>
<td>General Electric CJ805 (Long range jet)</td>
<td>454</td>
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<tr>
<td>Pratt &amp; Whitney JT-8D (Med. range jet)</td>
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<td>Rolls Royce Sprey MK511 (Med. range jet)</td>
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Table 5.2(a) Fuel Flow Rates

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<th>Engine</th>
<th>Fuel rate (kg/hr)</th>
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<td><strong>Allison T56-A15</strong> (Air carrier turboprop; mil. transport)</td>
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<td><strong>Allison T56-A 7</strong> (Air carrier turboprop; mil. transport)</td>
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<td><strong>Airesearch TPE-331</strong> (Gen. aviation turboprop)</td>
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<td><strong>Teledyne/Continental 0-200</strong> (Gen. aviation piston)</td>
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**Table 5.2(b) Fuel Flow Rates**

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<tr>
<th>Airplane Model</th>
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<td>727 - 200</td>
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<tr>
<td>737 - 200</td>
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<td>737 - 300</td>
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<td>737 - 400/500</td>
<td>28</td>
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<tr>
<td>747 - 200/300</td>
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<td>757 - 200</td>
<td>39</td>
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<tr>
<td>767 - 200/300</td>
<td>50</td>
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</table>

(This data is to be used for general planning only).

Table 5.3 Fuel Consumption Under Taxi Conditions
Other information relative to APU indicates that their fuel rates are from 120 lb/hr for small aircraft to 300 lb/hr for medium aircraft and 600 lb/hr for large aircraft.

So it appears that this consumption is not negligible in front of the consumption of an idle running engine in taxi conditions. It may be useful to recall that the APU is used mainly in modern aircraft to provide energy when the main engines are shut down or when they are to be started. In general at take-off, APU must be off.

5.2 Pollutant Emission by Aircraft Ground Operations

Recently emission data have been surveyed by various national organizations of environment protection. Data has been obtained from test at source, material balance studies and engineering estimates. The main factors considered have been:

- fuel consumption by stationary and mobile sources, consumption of solid wastes, evaporation of fuels and solvents.

The primary pollutants considered are:

- solid particles, nitrogen oxides, hydrocarbons and carbon monoxide.

Table 5.4 displays these emissions for the types of engines considered in Table 5.2.

Table 5.5 displays primary pollutant emissions for different types of aircraft operating either on ground (taxi-idle), approach (idle-approach) and take-off (full power).

5.3 Noise Emission

Many studies have been also realized during these last decades to estimate noise levels around airports. It is known that the main source of noise is engine operation at take-off and climb-out while landing and taxiing manoeuvres are a source of continuous background noise. Many improvements have been achieved with respect to noise emission by aircraft engines to meet the requirements imposed by national and international regulation.
<table>
<thead>
<tr>
<th>Engine and mode</th>
<th>Carbon Monoxide</th>
<th>Hydrocarbons</th>
<th>Nitrogen-Oxides(NO asNO2)</th>
<th>Solid particulates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pratt &amp; Whitney JT-9D (Jumbo jet)</td>
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<td></td>
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<tr>
<td>Taxi-idle</td>
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<td>27.3</td>
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<tr>
<td>Take-off</td>
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<td>720.0</td>
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<tr>
<td>Climbout</td>
<td>11.7</td>
<td>2.65</td>
<td>459.0</td>
<td>4.0</td>
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<tr>
<td>Approach</td>
<td>32.6</td>
<td>3.00</td>
<td>54.1</td>
<td>2.3</td>
</tr>
<tr>
<td>General Electric CF6 (Jumbo jet)</td>
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<td></td>
</tr>
<tr>
<td>Taxi-idle</td>
<td>51.7</td>
<td>15.4</td>
<td>3.6</td>
<td>0.04</td>
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<tr>
<td>Take-off</td>
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<td>1.3</td>
<td>540.0</td>
<td>0.54</td>
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<tr>
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<td>1.3</td>
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<td>0.54</td>
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<tr>
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<td>1.9</td>
<td>173.0</td>
<td>0.44</td>
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<tr>
<td>Taxi-idle</td>
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<td>98.6</td>
<td>44.7</td>
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<td>3.83</td>
<td>35.9</td>
<td>16.3</td>
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</table>

Table 5.4.(a) Modal Emission Factors
<table>
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<tr>
<th>Engine and mode</th>
<th>Carbon Monoxide</th>
<th>Hydrocarbons</th>
<th>Nitrogen-Oxides (NOx as NO2)</th>
<th>Solid particulates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lb/hr</td>
<td>kg/hr</td>
<td>lb/hr</td>
<td>kg/hr</td>
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<td>General Electric CJ805 (Long range jet)</td>
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<tr>
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\(^*\) Med. range jet

Table 5.4(b) Modal Emission Factors

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<th>Engine and mode</th>
<th>Carbon Monoxide</th>
<th>Hydrocarbons</th>
<th>Nitrogen Oxides (NOx as NO2)</th>
<th>Solid particulates</th>
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Table 5.4.(c) Modal Emission Factors

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<th>HC</th>
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<th>SP</th>
<th>CO</th>
<th>HC</th>
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<td>1.7</td>
<td>0.1</td>
<td>0.1</td>
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<td>0.1</td>
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<td>Turboprop</td>
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<td>0.1</td>
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<td>0.1</td>
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</tr>
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<td>0.1</td>
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<td>0.1</td>
<td>0.1</td>
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<td>0.1</td>
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<tr>
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<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td>Kite</td>
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<td>0.1</td>
<td>0.1</td>
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<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Hot Air Balloon</td>
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<td>1.7</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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</tr>
</tbody>
</table>

Table 6.5: Emission Factors and Fuel Consumption Rates by Aircraft Type and Model.
With respect to noise emission caused by taxiing manoeuvres, it is clear that the reduction of queues and waiting times while engines are on will have a direct and important influence on their diminution.

5.4 Fuel Conservation Practices and Procedure
First, it must be said that in general, the reduction of fuel burns will have a positive effect over pollutant and noise emissions. So the benefits obtained from a fuel conservation policy are strengthened by environment considerations. Four main strategies have been considered recently:

- operations with fewer engines while taxing;
- towing of aircraft between aprons and runway;
- optimization of landing roll and routing in taxiways;
- gate hold procedures and departure scheduling.

5.4.1 Current Practices for ground operations
These practices depend on the considered airport (configurations and ground equipments) and on the willingness of present airlines. Here a survey realized at DCA and IAD (source FAA-EE-82-8, March 1982) airports is reported.

A) Starting Engines during pushback
Braniff, Eastern, Trans World, United and U.S. Air start engines after pushback. Engine start during pushback is intended to reduce the time needed to move the aircraft from the gate to take-off. This action would save fuel and reduce emissions associated with APU operation if time from the gate is actually reduced. Table 5.6 illustrates the effect of engine start procedures on the length of time aircraft were required to hold before taxi for the B727 aircraft operating at DCA. The cumulative frequencies show the number of instances when the hold before taxi time intervals were equal or greater than the indicated intervals.

Engine start during pushback appears to enable B727 aircraft to begin to taxi approximately 15 seconds sooner than if the engines were started after pushback. A larger difference of at least 45 seconds was expected; however, the comparisons are fairly consistent for each time arrival. For example, the
## Table 5.6  Effect of Engine Start Procedure on Hold Before Taxi

<table>
<thead>
<tr>
<th>Hold Before Taxi Elapsed Time Intervals, Minutes: Seconds</th>
<th>Cumulative Frequency of Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start Engines After Pushback</td>
</tr>
<tr>
<td>00:00 - 00:14</td>
<td>32 Cases* 100%</td>
</tr>
<tr>
<td>00:15 - 00:29</td>
<td>32 100</td>
</tr>
<tr>
<td>00:30 - 00:44</td>
<td>30 94</td>
</tr>
<tr>
<td>00:45 - 00:59</td>
<td>26 81</td>
</tr>
<tr>
<td>01:00 - 01:14</td>
<td>18 56</td>
</tr>
<tr>
<td>01:15 - 01:29</td>
<td>14 44</td>
</tr>
<tr>
<td>01:30 - 01:44</td>
<td>8 25</td>
</tr>
<tr>
<td>01:45 - 01:59</td>
<td>6 19</td>
</tr>
<tr>
<td>02:30 - 02:29</td>
<td>4 12</td>
</tr>
<tr>
<td>02:30 - 02:59</td>
<td>3 9</td>
</tr>
<tr>
<td>03:00 - max.</td>
<td>3 9</td>
</tr>
</tbody>
</table>

* These columns give the cumulative frequency of cases for which elapsed times were equal or greater than indicated intervals.
delay after pushback exceeded 45 seconds for 81% of the 32 instances associated with airlines that typically start engines after pushback. This compares to delays exceeding 30 seconds for 82% of the 97 instances associated with airlines that typically start engines during pushback. Similar comparisons can be made for other delay intervals.

Delays after pushback exceeded 1 minute for 43 percent of the instances when engines were started during pushback and 56 percent of the instances when started after pushback. Delays exceeded two minutes approximately 12% of the time in either instance. It appears that some unplanned factor other than readiness to taxi was affecting the delay before taxi.

As stated above, there is a potential for fuel savings provided the pilots time their engine start procedures such that all engines are running at the time the pushback vehicle is disconnected from the aircraft.

The savings would amount to the fuel saved by shutting the APU down sooner than they would if they had waited until they had completed the pushback activity before starting their engines. The potential fuel savings shown in Table 5.7 are based upon the following assumptions:

The pilot was able to time starting his engines such that they were running and stabilized (ready to taxi) at the moment the pushback vehicle was disconnected and clear of the aircraft.

Delay after ready to taxi and aircraft movement would be the same for either practice.

APU’s would be shut-down immediately after the engines were started and stabilized.

The "start engines during pushback" strategy is not applicable to operations at Dulles airport.

B) Taxing out or in with one or more engines shut-down
With the exception of the GE CF6 series of engines (which have a very low idle power setting) aircraft operating at DAC and IAD are capable of taxiing...
<table>
<thead>
<tr>
<th>Airline</th>
<th>Fuel Savings (Kg)</th>
<th>Cost (79$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Florida</td>
<td>1,599</td>
<td>288</td>
</tr>
<tr>
<td>American</td>
<td>39,231</td>
<td>7,062</td>
</tr>
<tr>
<td>Braniff</td>
<td>16,815</td>
<td>3,027</td>
</tr>
<tr>
<td>Delta</td>
<td>25,150</td>
<td>4,527</td>
</tr>
<tr>
<td>Eastern</td>
<td>104,721</td>
<td>18,850</td>
</tr>
<tr>
<td>National</td>
<td>22,145</td>
<td>3,986</td>
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<tr>
<td>N. Central</td>
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<td>7</td>
</tr>
<tr>
<td>Northwest</td>
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<td>7,857</td>
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<tr>
<td>Piedmont</td>
<td>27,951</td>
<td>5,031</td>
</tr>
<tr>
<td>Republic</td>
<td>1,088</td>
<td>196</td>
</tr>
<tr>
<td>Trans World</td>
<td>28,399</td>
<td>5,112</td>
</tr>
<tr>
<td>United</td>
<td>30,548</td>
<td>5,499</td>
</tr>
<tr>
<td>U.S. Air</td>
<td>38,273</td>
<td>6,839</td>
</tr>
<tr>
<td>Western</td>
<td>1,409</td>
<td>254</td>
</tr>
<tr>
<td>TOTAL</td>
<td>381,409</td>
<td>68,583</td>
</tr>
</tbody>
</table>

Table 5.7 Potential Fuel Savings Starting Engines During Pushback DCA
at maximum gross weight with all engines at idle. As the gross weight becomes less (with less payload or fuel) the pilot compensates for the added thrust by the use of brakes.

When the pilot uses less than all engines for taxi, it would be expected that he would be required to compensate for the lost thrust by adding power on the remaining engines. This is true for many operations at IAD where the aircraft carry full fuel loads and hence have high take-off gross weights.

However, at DCA, where the average stage length is approximately 400 nmi, the aircraft are able to taxi on less than all engines at idle power. This fact has been verified by conversations with the airlines regarding the take-off gross weights of departing aircraft. Some of the power available versus power required calculations were marginal and as such, it is conceivable that in some instances, the pilots may be required to taxi at a higher power setting than idle when taxiing on less than all engines. In addition, since most fuel has been consumed before landing, additional power would not be required to taxi in on less than all engines.

Tables 5.8, 5.9(a) and 5.9(b) present estimates of the actual and potential fuel savings that could be achieved at DCA and IAD airports by taxiing in or out on less than all engines. The fuel savings are the difference between fuel consumed in the baseline estimate and the fuel which would be consumed if aircraft taxied in or out on less than all engines. The algorithm used for these calculations is as follows:

\[ \text{NOPS} \times \text{FFR} \times \text{TIM} \times \% = FC \]

Where \( \text{NOPS} \) = number of operations by airline by type of aircraft

\( \text{FFR} \) = Fuel flow rate for the power setting required based upon the average take-off gross weight by airline and type aircraft. This data was obtained from conversations with the airlines operators.

\( \text{TIM} \) = Time in mode adjusted by the time required to start-up or shut down an engine.

\( \% \) = Percent that a particular airline uses this procedure for taxi out or in.
<table>
<thead>
<tr>
<th>Airline</th>
<th>Aircraft Type</th>
<th>Actual Savings per Year (Kg)</th>
<th>Potential Savings per Year (Kg)</th>
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</thead>
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<tr>
<td></td>
<td></td>
<td>OUT</td>
<td>IN</td>
</tr>
<tr>
<td>QH</td>
<td>B 737</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>DC 9</td>
<td>420</td>
<td>1,290</td>
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<tr>
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<td>B 727</td>
<td>39,207</td>
<td>117,691</td>
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<tr>
<td>BN</td>
<td>B 727</td>
<td>18,207</td>
<td>26,923</td>
</tr>
<tr>
<td>DL</td>
<td>B 727</td>
<td>25,441</td>
<td>49,195</td>
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<td></td>
<td>DC 9</td>
<td>921</td>
<td>1,707</td>
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<tr>
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<td></td>
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<td>157,624</td>
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<tr>
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<td>B 727</td>
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<tr>
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<td>B 727</td>
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<td>B 727</td>
<td>7,504</td>
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<td>B 727</td>
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Table 5.8 Potential And Actual Annual Fuel Savings Due To Taxiing On Less Than All Engines At DCA (Based on 1979 Data).
<table>
<thead>
<tr>
<th>Airline</th>
<th>Aircraft Type</th>
<th>Actual Savings (Kg)</th>
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<tr>
<td></td>
<td></td>
<td>out</td>
<td>in</td>
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<tr>
<td>AA</td>
<td>B 727</td>
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<tr>
<td></td>
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<td></td>
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<td>DC 9</td>
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<tr>
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Table 5.9.(a) Potential And Actual Annual Fuel Savings Due To Taxiing On Less Than All Engines At IAD (Based on 1979 Data).
<table>
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<tr>
<th>Airline</th>
<th>Aircraft Type</th>
<th>Actual Savings (KG)</th>
<th>Potential Savings (KG)</th>
</tr>
</thead>
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<td></td>
<td></td>
<td>OUT</td>
<td>IN</td>
</tr>
<tr>
<td>TW</td>
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<td>0</td>
<td>47,281</td>
</tr>
<tr>
<td></td>
<td>B 747</td>
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<td>424</td>
</tr>
<tr>
<td></td>
<td>DC 9</td>
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<td>43</td>
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<td></td>
<td>L 1011</td>
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<td>B 727</td>
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<td>B 737</td>
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<td></td>
<td>B 747</td>
<td>0</td>
<td>212</td>
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<td>SSC</td>
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</tbody>
</table>

Table 5.9.(b) Potential And Actual Annual Fuel Savings Due To Taxing On Less Than All Engines At IAD (Based on 1979 Data).
\[ FC = \text{Fuel consumed.} \]

Potential fuel savings were derived by assuming all airlines use the procedures one hundred percent of the time.

### 5.4.2 Towing of aircraft between terminal area and runways

Towing of aircraft has been a common practice for many years, however it has been limited to:

- pushback maneuvers from the passenger terminal;
- towing over short distances within confined apron layout; or
- ferrying of empty aircraft between the terminal area and airlines maintenance facility.

Extended towing of loaded aircraft between the terminal and the runways has not been conducted, although it was proposed by the Massachusetts Port Authority for Boston-Logan International airport for noise abatement purpose.

In extended towing, an arriving aircraft would taxi to a conveniently located area, shut down its engines and then be connected to a tractor which would tow the aircraft to the terminal area. Similarly, a departing aircraft would be towed from its parking position to an area adjacent to its take-off point before aircraft engines are started. Because the fuel consumption rate of a tractor engine is much lower than that of a jet engine, reductions in fuel consumption could be achieved with towing. At the same time, the reduced utilization of aircraft engines would also result in some savings in engine maintenance costs.

The issues in the implementation of such towing operations are primarily concerned with safety, operational efficiency, and economics. These aspects have been discussed in great details by Fan.

At Zurich airport the environmental protection department has completed in 1991 a preliminary survey of operational towing, and has now formed a

A joint working group consisting of the airport authority and base airline and handling agent Swissair.

The survey says that in order to adapt to increased towing tractor operations, airports would have to adjust infrastructure by incorporating measures such as special return roads to avoid possible collisions with taxing aircraft.

Airlines would also have to work out who is legally in control of the aircraft when it is under tow. Pilots may wish to have electronic access to the towing vehicle’s brakes, and aircraft manufacturers would have to give certification to types of vehicles to ensure that towing aircraft with full loads does not inflict damage on landing gear systems. All in all there is a long way to go before operational towing becomes commonplace.

The survey included calculation with the following assumptions:

- Average taxiing-time: ten minutes,
- Take-offs: 210,000 (including general aviation and small jets).

The results were astonishing:

- Reduction of fuel: 12,700 t / annum,
- Reduction of emissions per year: NOx - 40t; HC - 210t; CO - 450t; CO2 - 41,500t.

The report concluded that SFr9 million ($6 million) would be saved at Zurich annually on fuel cost alone. But total investment costs would be SFr 45 million ($29.8 million), with an annual operating cost of SFr11 million ($7.3 million).

Note that environmental benefits are difficult to quantify in purely financial terms. It is difficult to say whether airports have the infrastructure for operational towing since, most aircraft technical problems are observed on engine start-up, which at a busy airport, where an aircraft is in a holding queue and then has to be towed away, could cause problems. Also the network of dedicated roads that the towing vehicles would need are not present at most airports.
The Zurich study has isolated three areas of infrastructure that would be necessary:

- Separation areas, road returns for tractors and parking areas.

It also says that a specific towing mission control may be required, ideally alongside apron control.

Note that no aircraft manufacturer has yet given approval for towing fully loaded planes anything more than short distances. Lufthansa did successful trials with a B747 freighter under supervision from Boeing, but this limited testing was stopped due to the absence of any official international rules or guidelines. In fact there is a need of certification for specific tractors due to the enormous forces that are involved when towing fully laden aircraft.

Swissair has been discussing the technical feasibility with Boeing, McDonnell Douglas and Fokker. It seems also that the economics of the whole operation would have to be very carefully examined before an airline could commit itself to such a heavy capital investment since one of MAN’s AM150 towbarless tractors, for example costs today about $500,000.

5.4.3 Planning Landing Roll turn-off and taxiing

Runway exit choice can be evaluated by comparing the exits of a common runway used by airlines located at one end of the terminal of an airport with exits used by airlines located at the other end of the terminal.

If one considers that a landing roll extends 2000 feet beyond the preferred exit and assumes that the additional distance on the runway resulted because the aircraft was travelling too fast to make the preferred exit turn safely, the 2000 feet could be travelled in approximately 35 seconds. Braking and reverse thrust forces would be reduced, and the fuel used to reach the more distant exit might not be very different from that which would have been used to make a nearly panic slow down for the turn.

Then the time required to taxi 2000 extra feet back towards the gates would be 100 seconds at 20 ft/sec (13.6 MPH) or 200 seconds at 10 ft/sec (6.8 MPH).
In various surveys it has been shown that the air carriers chose to use the runway which makes possible the use of the most efficient taxi route between the runway and the apron. It was not clear, however, that the inbound air carriers always adequately consider their ultimate destination on the apron. Outbound air carriers have appeared to consider this factor more closely. Substantial fuel savings would result from reducing taxiing on the apron. These savings could be achieved through more careful consideration of apron position when choosing which runway to use.

5.4.4 Gate Hold procedures

Fuel savings are being realized by the airlines by holding their aircraft at the origin airports when there are anticipated air traffic delays at the destination. Based upon the length of the anticipated delays, aircraft will either remain at the gate on ground power units (GPUs) or move to a

<table>
<thead>
<tr>
<th>Aircraft Type</th>
<th>Engines Cruise Power</th>
<th>Engines Idle Power</th>
<th>Engines Off APU Power</th>
<th>Engines Off GPU Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>B 747</td>
<td>405</td>
<td>50.7</td>
<td>2.4</td>
<td>0.08</td>
</tr>
<tr>
<td>DC 10</td>
<td>260</td>
<td>33.8</td>
<td>1.0</td>
<td>0.08</td>
</tr>
<tr>
<td>L 1011</td>
<td>277</td>
<td>39.6</td>
<td>1.0</td>
<td>0.08</td>
</tr>
<tr>
<td>B 707</td>
<td>242</td>
<td>27.2</td>
<td>N/A</td>
<td>0.08</td>
</tr>
<tr>
<td>DC 8</td>
<td>242</td>
<td>27.2</td>
<td>N/A</td>
<td>0.08</td>
</tr>
<tr>
<td>B 727</td>
<td>152</td>
<td>23.1</td>
<td>0.7</td>
<td>0.08</td>
</tr>
<tr>
<td>B 737</td>
<td>120</td>
<td>17.3</td>
<td>0.7</td>
<td>0.08</td>
</tr>
<tr>
<td>DC 9</td>
<td>101</td>
<td>15.4</td>
<td>0.7</td>
<td>0.08</td>
</tr>
<tr>
<td>BAC 111</td>
<td>87</td>
<td>13.4</td>
<td>0.7</td>
<td>0.08</td>
</tr>
<tr>
<td>YS 11</td>
<td>19</td>
<td>6.2</td>
<td>0.3</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Table 5.10 Consumption Rates (KG/MIN)
holding area where they shut-down their engines and operate on the aircraft’s auxiliary power units (APUs). Savings, of course, are based upon the length of delay and consist of the differences on fuel consumed at cruise in a holding pattern versus that consumed on the ground. These savings are shown in Table 5.10 by aircraft type for each minute the aircraft is able to avoid holding.

However, in the same ground, large savings should be achieved by perfect scheduling of departures in order to avoid departure queues with engines running.
CHAPTER SIX

Mathematical Programming Approach of the Ground Scheduling Problem

6.1 Introduction
In this chapter we consider a mathematical programming approach of the Ground Scheduling Problem. Possible mathematical formulations are considered and classical mathematical programming solution techniques are discussed and assessed in view of their implementation in real time for real sized problems.

First, with the objective to optimize the whole air terminal system, both outbound and also inbound flight are considered as part of a global decision problem. Since this problem proves intractable, only the Departure Scheduling Problem (DSP) is considered further. Exact solution approaches as well as heuristic methods and knowledge-based techniques are then described for solving this problem. It appears that only heuristic methods of the greedy type are consistent with real time management of departures.

6.2 A Global Model.
To be complete, the optimization of operations at air terminal systems should cover departure as well as arrival operations so that inbound and outbound flows could be managed in an efficient way (cost and delays of different nature). This efficiency should be the result of the co-ordination of these two operations.

To achieve this overall objective some points must be fixed:

- Definition of the limits of the air terminal system,

- Construction of a global index of performance covering airborne and ground delays,

- Definition of the operating conditions:
existence of 4D navigation systems and ATC to regulate inbound traffic.

existence of ground traffic control systems for arriving and departing aircraft.

6.2.1 The Structure of the Terminal System.
The terminal system is composed of its air side and its ground side with terminal approaches and runways as interfaces. In general arriving and departing paths are segregated to the airport airside, the runways and the parkings stands being their connection points. So we get a graph structure such as (Fig. 6.1).

Each arc is characterised by its geographical position and may be used by aircraft with different characteristics (size, airspeed, ground speed,...).

6.2.2 The Global Objective Function.
Let $T$ be the time-period considered. Let $N_a$ be the number of arriving aircraft during this period and $N_d$ be the number of departing aircraft during this same period which should in theory cover a day's operation or at least a peak period.

Supposing that arriving aircraft which are delayed must wait near the TMA entry gates, let $C_{a}^{k} (\tau)$ be the cost of a delay of one unit of time (u.o.t.) for the $k^{th}$ arriving aircraft at its holding position. This cost is composed of two terms:

$$C_{a}^{k} (\tau) = C_{t}^{k} \cdot \tau + C_{f}^{k} \cdot \tau$$

where

$C_{t}^{k}$ is the value of one u.o.t. which is considered common to all arriving aircraft of the same class (generally, larger aircraft cost more).

$C_{f}^{k}$ is the value of the fuel burned by the $k^{th}$ aircraft at holding point during one u.o.t. This value depends on the type of this aircraft and on the altitude of the hold.

In general holding stations are filled in a first come - first out basis, considering successive available levels of holding. See Fig. 6.2.
Figure 6.1 Structure of the terminal system.
However it is considered here that holding levels will be assigned in an optimised way to each delayed aircraft.

Let \( C_d^h (\tau) \) be the cost of a departure delay of \( \tau \) u.o.t., at the parking stand of the \( h^{th} \) departing aircraft.

A cost function \( C_d^h (\tau) \) will be such that:
\[
\forall \tau \geq 0 : \quad C_d^h (\tau) \geq 0 \quad \text{and} \quad \frac{d}{d\tau} C_d^h \geq 0
\]
and if a maximum delay is introduced, we have: see (Fig. 6.3).

The global objective function to be minimised is then:
\[
C = \sum_{k=1}^{N_a} C_a^k (\tau_a^k) + \sum_{h=1}^{N_d} C_d^h (\tau_d^h)
\]
where
\[
\tau_a^k \text{ is the delay incurred by the } k^{th} \text{ arriving aircraft,}
\]
\[
\tau_d^h \text{ is the delay incurred by the } h^{th} \text{ departing aircraft.}
\]

Let
\[
T_a^k \text{ be the desired arrival time for the } k^{th} \text{ aircraft at the runway threshold,}
\]
\[
\ell_a^k \text{ be its assigned arrival time,}
\]
\[
T_d^h \text{ be the desired departure time for the } h^{th} \text{ aircraft from the runway,}
\]
\[
\ell_d^h \text{ be its assigned departure time.}
\]

Then:
\[
\tau_a^k = \ell_a^k - T_a^k \quad \text{and} \quad \tau_d^h = \ell_d^h - T_d^h
\]

6.2.3 Decision Variables and Restrictions

The decision variables which are chosen here are the instants
\[
\ell_a^k, \quad k = \{1, ..., N_a\} \quad \text{and} \quad \ell_d^h, \quad h = \{1, ..., N_d\}.
\]

They must satisfy direct and indirect restrictions.
Figure 6.2 Holding Policy.
In general the cost functions $C_d^k$ and $C_d^l$ are continuous convex functions.

$$\frac{d}{dt} C_d^3 \geq 0$$

Figure 6.3 Cost of a departure delay.
Direct restrictions:
Maximum delay restrictions:
\[ T^k_a \leq t^k_a \leq T^k_a + t^k_a \max \quad k=\{1,\ldots,N_a\} \]
\[ T^h_a \leq t^h_a \leq T^h_a + t^h_a \max \quad h=\{1,\ldots,N_d\} \]
Minimum separations at the runway:
- Between arrivals: \( t^h_a - t^k_a \geq s^h_{k,a} \) if \( t^h_a > t^k_a \)
- Between departures: \( t^k_a - t^h_a \geq s^k_{a,h} \) if \( t^k_a > t^h_a \)
- Between departures and arrivals:
\[ t^k_a - t^h_a \geq s^h_{k,a} \] if \( t^k_a > t^h_a \)
\[ t^h_a - t^k_a \geq s^k_{a,h} \] if \( t^h_a > t^k_a \)

where \( s^h_{kj} \), \( k=\{1,\ldots,N\} \), \( h=\{1,\ldots,N_d\} \), \( i \in \{a,d\} \), \( j \in \{a,d\} \) are minimum separations taking into account standard minimum time separations between aircraft of given categories and standard minimum distance separations converted into time separations using nominal speeds between operating aircraft at the runway threshold (see Appendix 3).

Indirect restrictions:
These restrictions are relative to "en-route" minimum separations either on converging / diverging airpaths or taxiways and parking areas.

Supposing that each arriving aircraft follows an optimized descent (profile, velocity), its position at instant \( (t) \) is:
\[ E\hat{M}_k(t) = E\hat{R}_k + \int_{t^k_e}^t \hat{v}_a(\tau) \cdot d\tau \quad \text{if} \quad t^k_e \leq t \leq t^k_a \]

where \( \hat{v}_a \): ground speed of arriving aircraft (k).
$M_k(t)$: spatial position of arriving aircraft (k) at time (i).

$t_0^k$ is the instant at which aircraft (k) enters the TMA.

$E$ is the runway threshold, $I_k$ the entry gate and $O_h$ the exit gate for aircraft (k) (see Fig. 6.4).

Also we have:

$M_k(t) = I_k$ if $t < t_0^k$ and $M_k(t) = E$ if $t > t_0^k$

Let $\xi(t) = \{ k \mid k \in \{1, \ldots, Na\}, M_k(t) \neq E \text{ and } M_k(t) \neq I_k \}$

$\forall k, k' \in \xi(t): ||M_kM_k'|| \geq S_{kk'}^{\xi}$ \hspace{1cm} (6.1)

For departing aircraft we have:

$E\overline{M}_h(t) = \int_{t_d^h}^{t_e^h} \overline{v}_d(\tau) \ d\tau \text{ with } t_d^h \leq t \leq t_e^h$

Let $L(t) = \{ h \mid h \in \{1, \ldots, Nd\}, M_h(t) \neq E \text{ and } M_h(t) \neq O_h \}$

where $t_e^h$ is the instant at which aircraft $h$ leaves the TMA at gate $O_h$.

Then:

$\forall h, h' \in L(t): ||\overline{M}_h\overline{M}_h'|| \geq S_{hh}^{\xi}$ \hspace{1cm} (6.2)

Conditions (6.1) and (6.2) can also be expressed as initial separation conditions either at instants $(t_0^k, t_0^k)$ and $(t_0^k, t_0^k)$ with additional speed conditions. In fact, these sets of constraints should be considered at discrete instants all over time period T.

With respect to taxiways, overtaking conditions must be considered.

Let $L_{hh'}$ be the common track for departing flight $h$ and $h'$,

if $t_d^h > t_d^{h'}: t_d^h - \frac{L_{hh'}}{W_h} \geq t_d^{h'} - \frac{L_{hh'}}{W_h} + t_{\min}^{hh'}$ \hspace{1cm} (6.3)

where $W_h$ is the rolling speed for departing aircraft $h$ and $t_{\min}^{hh'}$ is
Figure 6.4 Position of aircraft

\[ E\hat{M}_k(t) = \begin{bmatrix} x_k(t) \\ y_k(t) \\ z_k(t) \end{bmatrix} \]
such that:

\[ t_{\min}^{hh'} = \frac{f_{\min}^{hh'}}{W_h} \]

\( f_{\min}^{hh'} \) is the minimum distance between the classes of aircraft \( h \) and \( h' \).

### 6.2.4 Complexity of the Global Optimisation Problem.

So we get a very large scale and complex mathematical programming problem under the standard form:

\[
\begin{align*}
\min & \quad C \\
\text{subject to} & \quad t_d, t_a \\
\text{with} & \quad (t_d, t_a) \in \mathcal{F}
\end{align*}
\]

where \( \mathcal{F} \) is the feasible set.

This problem has difficult features such as: non-linear function combinatorial aspects, large number of restrictions (active or not) and large number of decision variables.

No known solution approach exists to tackle directly such a difficulty. However one must recognize that for this problem the mathematical optimality of a solution has little meaning in practice since for a long time, even with the use of sophisticated 4D navigation systems, air traffic flows will contain an important random component. So the flexibility of a non optimum but feasible solution strategy should be preferred to a cumbersome and computer time consuming "optimum" solution which should be re-run at each noticeable discrepancy between planned and actual conditions.

Different techniques can be considered to reduce the complexity of this problem:

- Decomposition, separation, aggregation, linearisation, reduction,...
Among them in the next sub-section we consider the application of the separation and linearisation techniques.

6.3 An Optimisation Approach for the Departure Scheduling Problem

Here the global management problem is split in two subproblems:

- a scheduling problem for arriving aircraft,
- a scheduling problem for departing aircraft.

A priority principle for arriving aircraft has been invoked so that the first of these two subproblems could be solved without any concern for the second one. Then the solution of this first problem constitutes a set of imposed constraints for the second scheduling problem, these being the occupation times of the runways and the parking stands by arriving aircraft. A "gap" distribution is thus presented to the departing aircraft.

6.3.1 Mathematical Formulation of the Departing Scheduling Problem.

We consider that the objective is here to minimise the total delay incurred by the set of departing aircraft:

\[
C_d = \sum_{h=1}^{N_d} (t_d^h - T_d^h) \quad \text{with} \quad t_d^h \geq T_d^h, \quad h = \{1, ..., N_d\}
\]

Here also, the natural decision variables are the instant of departure at the runway threshold. However, to make the formulation of the time constraints related with the allowed departure gaps, more practical, new decision variables may be introduced:

\[
x_{ij}^h = \begin{cases} 
1 & \text{if the } h^{th} \text{ aircraft depart using gap (i) in position (j)}, \\
0 & \text{otherwise.}
\end{cases}
\]

So we have the following restrictions to be satisfied;

\[
T_d^h \leq t_d^h \leq T_d^h + \Delta_d \text{ max} \quad (6.4)
\]

where \( \Delta_d \text{ max} \) is the maximum allowed delay for the \( h^{th} \) departing aircraft.

\[
\sum_{h=1}^{N_d} \left( \sum_{j} x_{ij}^h \right) \cdot t_d^h \leq d_i \quad i = \{1, ..., I\} \quad (6.5)
\]
where
\( r_{h}^{d} \) is the runway occupancy time by the \( h^{th} \) aircraft,
\( d_{i} \) is the duration of the \( i^{th} \) gap and
\( I \) is the number of gaps considered.

\[
 x_{j}^{d} \cdot (d^{j} + \bar{d}^{j}) \leq x_{j}^{d} \left( \sum_{l \neq h} x_{j-1}^{l} \cdot (d^{l} + \bar{d}^{l}) \right)
\]

\[
 x_{j}^{d} \cdot (d^{j} + \bar{d}^{j}) \leq x_{j}^{d} \left( \sum_{l \neq i} x_{j+1}^{l} \cdot \bar{d}^{l} \right) \quad (6.6)
\]

\[
 x_{j}^{d} \cdot (d^{j} + \bar{d}^{j}) \leq T_{i}^{M}, \quad i = \{1, ..., I\}
\]

\[
 x_{j}^{d} \cdot \bar{d}^{j} \leq x_{j}^{d} \cdot T_{i}^{m}, \quad i = \{1, ..., I\}
\]

where \( T_{i}^{m} \) and \( T_{i}^{M} \) are the begin and end time of gap \( i \).

\[
 x_{j}^{d} \cdot x_{j+1}^{d} \cdot \theta_{\min}^{h} \leq x_{j}^{d} \cdot x_{j+1}^{d} \cdot (\bar{d}^{j} - \bar{d}^{j}) \quad (6.7)
\]

\[
 \sum_{i} \sum_{j} x_{j}^{d} = 1, \quad h = \{1, ..., Nd\} \quad (6.8)
\]

- Condition (6.4) corresponds to the assumption which is made in this study that from commercial considerations, the departure time (discounting the taxiing delay) cannot happen before a published timetable and that its delay cannot be larger than a maximum level.

- Condition (6.5) is relative to the capacity of each gap: the total occupancy of a gap cannot be larger than its own duration.

- Condition (6.6) ensures that the take-off of an aircraft takes place within a departure time-gap.

- Condition (6.7) is relative to the minimum separation standards at take-off.
• Finally, condition (6.8) indicates that each departing aircraft must be assigned a position in a particular gap.

These above restrictions are basic and to them other specific conditions must be added. For instance it may be necessary to take into account airway capacity restrictions which may impose additional delay for departing aircraft.

6.3.2 Analysis of the Departing Scheduling Problem (DSP)

So we have formulated a mixed - integer mathematical programming problem. Its Boolean variables \( x_i^h \) confer on it a combinatorial nature while to each 0-1 partial solution corresponds a classical linear programming problem.

In general, the approaches to solution for this class of problems adhere to methods which take advantage of peculiarities of their formulation. Two classes of methods have been considered from the point of view of computer time:

- Exponential time algorithms for which the computer time required to reach the solution increases exponentially with the "size" of the problem (here for instance \( N_d \)). This is the case of enumeration algorithms which will consider at least \( N_d! \) candidate solutions. This class of algorithms is in general applied to very small size problems and is discarded for real size ones (\( 20! = 3.5 \times 10^{20} \)).

- Polynomial time algorithms for which the computer time required to reach the solution increases "slowly" with the size of the problem: \( t_c = k \cdot (\text{size})^p \)

Polynomial-time algorithms of degree 1 or 2 are considered in general to be efficient from this point of view.
The modern Theory of Complexity\footnote{Karp, R. M., 1975.} classifies decision problems also in two classes: P (polynomial) and NP (non polynomial) problems according with the existence of polynomial time solution algorithms. Those problems for which exponential time enumerative algorithms are the unique way to optimum solution, are called NP-complete.

Unfortunately, the scheduling problem considered in this section is a special case of the n jobs / 1 machine scheduling problem (jobs = departures, machine = runway) which has been recognised to belong to the class of NP-complete problems.

6.3.3 Exact Solution Methods for the DSP

Two classes of organized exhaustive search methods can be considered here to solve exactly the DSP problem:

- Backtrack Programming,
- Branch and Bound programming.

A) Backtrack Programming\footnote{Goodman, S. E., and Hedetniemi, S. T., 1977.}

This technique develops a systematic search among the \( N_d \) candidate solutions by successive elimination of non feasible sets of solutions and memorization of the best complete solution encountered until the current stage. A binary tree can be constructed to represent the search process, see (Fig. 6.5).

From level \( i \) to level \( i+1 \) a new binary variable is fixed either to (0 or 1).

Complete solutions are obtained at each leaf of this tree and a linear programming problem must be solved to fix the timing which leads to the minimum total delay allowed by the current binary solution.

This technique is in general easy to code and doesn’t need a large amount of computer memory but it is computer time consuming since the "op-
The "optimum" solution is definitively obtained when the binary tree has been entirely searched.

So, this technique cannot be considered as a candidate solution approach for the DSP which in a real time context should be rerun repetitively and therefore needs a short response time.

**B) Branch and Bound Programming**

This technique has been successfully used to solve medium size combinatorial problems such as the travelling Salesman Problem and various workshop Scheduling problems. This technique is based on four basic rules:

- a separation rule which allows the partition of a feasible set of solutions $\varphi$ in two subsets $\varphi_1$ and $\varphi_2$ ($\varphi = \varphi_1 \cup \varphi_2$, $\varphi_1 \cap \varphi_2 = \emptyset$) so a search tree is built up.
- a shifting rule to move along the search tree.
- an evaluation rule to get a lower bound for the cost of solutions in a subset $\varphi_i$.
- a simple construction rule for a feasible solution in each subset $\varphi_j$.

Let $\tilde{C}_j$ be the performance (total delay) of a feasible solution in $\varphi_i$ and let $C^*_i$ be a lower bound for the performance of each feasible solution in $\varphi_i$. Then if $C^*_i > \tilde{C}_j$ the whole subset $\varphi_j$ may be deleted from the search tree.

So in this case the whole binary tree does not have to be built up and only a small number of complete solutions must be evaluated (by resolution of a linear programming problem) while large solution subsets are successively abandoned.

However, active solution subsets must be memorised, this may lead to a need of large memory storage capability.

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Figure 6.5  Search Tree for Backtrack.

Level (0):

Level (1):

Level (2):

Level (3):

Search Path

Level (n):
Complete solution are constructed
Each of these four rules may be implemented in different ways to cope with a given problem. So, the efficiency of the method will depend on the skilfulness of the designer of the algorithms. At this point heuristics may be used to chose the shifting rule for this exact method (see Fig. 6.6).

This technique has been used by Bianco to solve the arriving scheduling problem in a 4D context* which is less constrained that the Departing Scheduling Problem under study here. However, Bianco found CPU time of 373 seconds for a 30 aircraft ASP problem and 1956 seconds for a 40 aircraft ASP problem carried out on a Mainframe computer. So it appears that the Branch and Bound approach is not compatible with real time requirements.

Anther solution approach, the Dynamic Programming Approach ** shows the same deficiencies since it leads to a search processing an extremely large solution tree.

6.4 Approximate Solutions for the DSP

Since exact methods are too time consuming to be considered for practical utilization in a real time context, approximate solution strategies may be considered if they provide a satisfactory trade-off between CPU time requirements and solution efficiency. Many heuristic approaches have been developed to get acceptable solutions for NP-complete decision problems. Two main directions are available today:

6.4.1 Greedy solution approaches

These approaches are derived in general from the Branch and Bound technique where only one path from the root of the search tree to a unique leaf is followed. A rule is thus established to select at each step the more attractive partial solution. This approach leads in $N_d$ steps to a local optimum solution which may be more or less distant from the global optimum solution. In general, heuristics are analysed to detect their worst-case behaviour and their performance variability. A typical heuristic ap-


proach to solve scheduling problems at service stations is the so called First Come First Served (FCFS) approach which requires minimum computer resources.

This approach, as any other heuristic method, can provide in specific situations exact solutions. In Appendix 4 the theoretical case of an heuristic for the classical one - machine scheduling problem with due dates is considered. Here we consider a set of \( N_d \) departing aircraft ordered according to a FCFS policy and presenting a common minimum separation time \( S \) and we show that the solution obtained from this policy is locally optimum.

Let \( T_{d}^{h} \) and \( t_{d}^{h} \) be the desired and the effective departing time for the \( h^{th} \) scheduled departing aircraft. The total delay is given by:

\[
C^* = \sum_{h=1}^{N_d} (t_{d}^{h} - T_{d}^{h})
\]

Suppose that aircraft \( h \) and \( h+k \) exchange their rank in the departure grid. Two cases must be considered:

1) \( T_{d}^{h+k} < T_{d}^{h} \): In this case, define \( C^k \) as:

\[
C^k = \sum_{l \neq h}^{l \neq h+k} (t_{d}^{l} - T_{d}^{l}) + (t_{d}^{h+k} - T_{d}^{h+k}) + (t_{d}^{h} - T_{d}^{h+k})
\]

We have also

\[
C^k = \sum_{l \neq h}^{l \neq h+k} (t_{d}^{l} - T_{d}^{l}) + (t_{d}^{h} - T_{d}^{h}) + (t_{d}^{h+k} - T_{d}^{h+k})
\]

or

\[
C^k = C^*
\]

2) \( T_{d}^{h+k} > T_{d}^{h} \)

In this case aircraft \( h+k, h+1, h+2, ..., h+k-1, h, h+k+1, ..., N_d \) are delayed by \( (T_{d}^{h+k} - T_{d}^{h}) \) while aircraft \( h+k \) departs without any delay at time \( t_{d}^{h} \).
\[ \varphi = \varphi_1 \cup \varphi_I \]
\[ \varphi_1 \cap \varphi_I = \emptyset \]

\[ C_3 > \min \{ \tilde{C}_2, \tilde{C}_2, \tilde{C}_3 \} \]
\[ C_4 > \min \{ \tilde{C}_2, \tilde{C}_3, \tilde{C}_4 \} \]

\[ \bullet \text{ : active nodes} \]

Figure 6.6 Branch and Bound search tree.
Thus here: \[ C^k > C^* \]

So we can conclude that when there is a common minimum separation time at the runway for departure, the FCFS strategy generates a local optimum sequence of departing aircraft. Note that no consideration has been made here of other constraints (arriving aircraft, taxiing and parking) so that this approach may be less simple that it appears at first glance.

In the literature*, greedy heuristics applied to real size scheduling problems have in general provided solutions which are about 20% less satisfactory in terms of waiting times or cost than the exact optimum solution. This performance appears to be hard to improve without the introduction of intricate computations which may make the whole method vulnerable to specific data leading to a worst case situation**.

Recently many hopes have been directed to a new tool for decision makers: expert systems or knowledge-based computer systems (KBS) which adopt fifth generation programming languages (prolog and lisp) to use Artificial Intelligence techniques to find an acceptable solution. A survey of KBS for transport planning and operations applications has been proposed by Taylor recently***, showing the interest of this approach for solving graph related transportation problems. Also, the French CENA (Center d'Études de la Navigation Aérienne) has developed a prototype system which generates schedule proposals to air traffic controllers.

Briefly, the structure of an expert system is given in Fig. 6.7.

No known application of KBS to the DSP exists until now.

KBS systems have been initially introduced to solve static diagnosis problems in medicine, mechanics and chemistry. They have shown poor

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capabilities with highly constrained real time decision problems since the search techniques used by inference machines remain time consuming.

Another important difficulty is relative to the generation of the "expert" knowledge to be stored in the knowledge base.

Is there any "rule" to be retained from practical or theoretical considerations which indicates how to chose the next aircraft to be directed to the runway for departure?

While such rules may exist for low traffic situations where the decision problem may be simple and manageable efficiently by a human operator, for higher traffic situations, characterized by complex interactions and a large number of events, no detectable individual rules can be made out beyond trivial rules of thumb which, while guaranteeing feasibility, generate large penalties for users. So, progress with this approach seems very questionable if generic KBS systems are to be used.
CHAPTER SEVEN

An Heuristic Approach for On-line Scheduling of Departing Aircraft.

7.1 The basic idea.

In the previous chapter we have considered the scheduling problem of departing flights in a static context with perfect information. It has been shown that for realistic problems, the search for the optimum solution is intractable by computer and that an heuristic or knowledge based approach should be used. We recall here that in the Operations Research literature an heuristic method contains the following ingredients:

- it is a search method for a decision problem,
- it is not exact since in general it doesn't consider exhaustively the feasible solution set.
- it applies some clear principles of local optimality,
- it provides a feasible solution at low computation cost,
- the proposed solution is understandable and checkable for local optimality by decision makers, justifying their belief in its performance.

However in a 4-D guidance context, the traffic situation evolves dynamically and predictions relative to inbound and outbound flights are periodically updated. So an heuristic approach for the implementation in real time must be designed to cope with this problem. Many parameters must be adequately chosen to guarantee the effectiveness of the method:

- choice of an horizon for real time scheduling,
- choice of an index of performance,
- choice of a sampling period for decision making,
- choice of a search method.
These points are discussed in this chapter and an approach to a solution is proposed. This solution is based on the improvement of a greedy (FCFS type) heuristic method for locally optimum solutions.

7.2 Selection of the Instants of decision

Let \( t_{dk} \) be an instant of decision such that a tentative departing schedule is built-up over a span of time \([ t_{dk}, t_{dk} + T ]\) using some receding horizon heuristic approach. Two important questions must be answered:

- when will the next decision time \( t_{dk+1} \) occur?
- what is the span of the optimization horizon?

Suppose that we have \( S \) stands from which \( V \) classes of aircraft (with respect to roll-out speeds) can depart to the beginning of the runway. So we have the following direct rolling out times: \( t_{sv} \), \( s = \{ 1, \ldots, S \} \), \( v = \{ 1, \ldots, V \} \).

Let \( T \) be the prediction horizon for arriving aircraft (and gap distribution), let \( t_{\min} \) (\( t_{\max} \)) be the minimum (maximum) of \( t_{sv} \) over the effective departing aircraft during \([ t_{dk}, t_{dk} + T ]\):

\[
\begin{align*}
\text{t} \min &= \min_{s=1,\ldots,S} \min_{v=1,\ldots,V} t_{sv} \\
\text{max} \quad \text{max} \\
\end{align*}
\]

(7.1)

such that there exists a departing flight from stand \( s \) with a \( v \) class aircraft over \([ t_{dk}, t_{dk} + T ]\).

Here a principle is proposed which proceeds from practical considerations for the applicability of the proposed method.

**Principle:** The selection of decision instants must be made such that aircraft already in ground movement will not be affected by the decisions taken at future instants of decision.

Consider the following scheduling representing two successive decision instants, different stands and roll-out speed classes of aircraft, see Fig. 7.1.

From the Fig. 7.1, it appears that this principle will be satisfied if the following condition is fulfilled:

\[
\begin{align*}
\text{t}_{dk+1} &\geq \text{t}_{dk} + t_{\max} - t_{\min} \\
\end{align*}
\]

(7.2)
Figure 7.1 Non interaction principle (different stands positions and roll-out speed).

Here: v=3, s=3
Since updates about predictions for gap distributions will be delivered at a frequency of $1/\tau$ at instants $t_{ue}$ (with $\tau << T$ and $t_{ue+1} = t_{ue} + \tau$) and since it is supposed that the best estimation for future gap distribution is the latest, $t_{dk+1}$ should be taken as:

$$t_{dk+1} = \min t_{ue} \text{ such that } t_{ue} \geq t_{dk} + t_{\text{max}} - t_{\text{min}}$$  \hspace{1cm} (7.3)

This is represented in Figure 7.2.

Some interesting observations must be made here:

- 1) Every instant of decision for the real-time scheduling problem of departing aircraft is a sampling time of the update process of estimation of the gap distribution.

- 2) If the roll-out times are all equal, the next instant of decision is the next sampling time ($t_{dk+1} = t_{dk} + \tau$).

- 3) It is not useful to have a sampling period for the estimation process less than $t_{dk} + t_{\text{max}} - t_{\text{min}}$, since the intermediate estimation will not be taken into account in the next decision process. Thus, $\tau$ should be such that:

$$(\tau) \text{ is minimum}$$

with

$$\tau \geq \max t_{sv} - \min t_{sv}$$ \hspace{1cm} (7.4)

$\quad v = 1, \ldots, V \quad s = 1, \ldots, S$

and $\tau << T$

### 7.3 Selection of the span of optimization horizon

If at instant $t_{dk}$ a tentative solution is proposed for the scheduling problem over an horizon $[ t_{dk}, t_{dk} + \delta T ]$, what will happen with the delayed aircraft at instant $\delta T$? It is clear that the optimality or near-optimality of the tentative solution will be largely dependent on the total number of delayed aircraft at the terminal instant of the horizon.
Figure 7.2  Selection of Decision Times.

Update sampling of time.
We consider that beyond time $t_{dk} + T$, a mean pattern of gaps is predicted from arriving time-tables and / or historical data.

- Let $A_k$ be the set of aircraft wanting to depart during period $[t_{dk}, t_{dk} + T]$.
- Let $Q_k$ be the set of waiting aircraft at their stands at time $t_{dk}$, if we allocate these aircraft $(A_k \cup Q_k)$ over a period starting at time $t_{dk}$ on a FCFS basis, the last of these aircraft to take-off will be departing at time $t_{dk} + \delta T$.

If $\delta T$ is greater than $T$, aircraft desiring to depart between $T$ and $\delta T$ will be ignored, however, these aircraft will be taken into account in subsequent decision instants so that this approximation will be corrected when more accurate data over future gap distribution will be available, see Figure 7.3.

### 7.4 Determination of the mean pattern of gaps.

Let $n_j$ be the expected number of aircraft of type $j$ (with respect to their occupancy time of the runway at landing) planned to arrive during a period $[t_{dk} + T, t_{dk} + \delta T]$ where $\delta \geq 2$, $j = \{1, \ldots, M\}$.

We consider the auxiliary entropy problem given by:

$$\max \sum_{i=1}^{M} \sum_{j=1}^{M} T_{ij} \log \left( \frac{T_{ij}}{P_{ij}} \right) \quad (7.6)$$

Such that,

$$\sum_{i=1}^{M} T_{ij} = n_j \quad (7.7)$$

$$\sum_{j=1}^{M} T_{ij} = n_i \quad (7.8)$$

$$T_{ij} \geq 0 \quad (7.9)$$

where $P_{ij}$ is the a priori probability of having an arriving aircraft class $i$ followed by an arriving aircraft of class $j$ ($P_{ij} \geq 0 \land \sum_{ij} P_{ij} = 1$).
Figure 7.3 Definition of the span of optimization.
The solution of this problem is of the form:

\[ T_{ij} = r_i s_j T_{ij}^o \quad \text{with} \quad T_{ij}^o = P_{ij} \sum_k n_k \]

Where \( r_i \), \( s_i \) are positive coefficients.

Various algorithms exist to solve this problem (to find the \( r_i \) and \( s_i \) coefficients). For instance, the algorithm of Furness is such as:

\[
T_{ij}^{(1)} = \frac{n_i}{\sum_k T_{ik}^o} \cdot T_{ij}^o
\]

\[
T_{ij}^{(2n)} = n_j \cdot \frac{T_{ij}^{(2n-1)}}{\sum_k T_{ik}^{(2n-1)}}
\]

\[
T_{ij}^{(2n+1)} = n_i \cdot \frac{T_{ij}^{(2n)}}{\sum_k T_{ik}^{(2n)}}
\]

A theoretical proof of convergence of this algorithm is given*, while in practical terms few interactions are necessary to get the unique solution of this problem.

Then, \( P_{ij} = \frac{T_{ij}}{\sum_k n_i} \) is the a posteriori to have an arriving aircraft of class \( i \) followed by an arriving aircraft of class \( j \).

Let \( d_{ij} \) be the minimum separation time at landing between aircraft of class \( i \) and \( j \) (in this order), the total runway occupancy time during period \([ t_{dk} + T, t_{dk} + \delta T ]\) is given by:

Let $\bar{D}$ be the estimated duration of a burst of arriving aircraft during the above mentioned period of time, this duration is supposed here to be characteristic of the traffic control strategy used at the moment. So the predicted number of gaps during the period $[t_{dk} + T, t_{dk} + \delta T]$ is then:

$$N_s = \frac{T_{tot}}{D}$$

(7.13)

and the estimated mean duration of a gap is then:

$$\bar{d} = \frac{(\delta - 1) T - T_{tot}}{T_{tot}} \cdot \bar{D}$$

(7.14)

This estimation of the mean gap pattern during the end of the receding optimization horizon may seem quite rough, however it allows account to be taken in a coherent way of aircraft delayed at the end of the actual prediction horizon $t_{dk} + T$.

### 7.5 The Objective Function

The scheduling must minimize a performance function of the form:

$$P_k = \sum_{i \in A_k \cup Q_k} W_i^k \cdot (\theta_i^k - \hat{\theta}_i)$$

(7.15)

Where $\hat{\theta}_i$ is the desired departure time from the stand for the $i^{th}$ aircraft, $\theta_i^k$ is the assigned departure time at time $t_{dk}$ to the $i^{th}$ aircraft and $W_i^k$ is a weight which characterize the importance attributed to delays for aircraft $i$ by the controllers.

If $W_i^k$ is chosen constant over $(i)$ and $(k)$, $P_k$ reduces to the total delay for aircraft of $A_k \cup Q_k$. However it seems necessary to introduce different weights for aircraft of different sizes with different payloads (passenger, freight ...).
For instance we could have:

**For passengers aircraft:**

\[ W_i = W_{\text{min}} + \delta \cdot N_i \]  

(7.16)

where \( \delta \) is a factor of proportionality and \( N_i \) is the number of passengers in flight (i).

Note that if \( W_{\text{min}} \) is null, \( P_k \) reduces for passenger aircraft to the total delay for departing passengers in flights of \( A_k \cup Q_k \).

Also, small aircraft or poorly loaded widebodies will be largely penalised by this weighting scheme, so to avoid a too large penalty, weights can be updated such that:

1) for aircraft \( i \in Q_k \): 

\[ W^k_i = W_{\text{max}}^P \text{ if } t_{d_k} - \hat{\theta}_i > D_{\text{max}}^P \]

where \( D_{\text{max}} \) is a delay threshold level beyond which higher priority is assigned to the delayed aircraft.

2) for aircraft \( i \in A_k \):

\[
\text{While } t < \hat{\theta}_i + D_{\text{max}}^P : W_i^A = W_i^k \\
\text{When } t > \hat{\theta}_i + D_{\text{max}}^P : W_i^A = W_{\text{max}}^P
\]

(7.17)

**For freight aircraft:**

\[ W_i = W_{\text{min}} \text{ while } t - \hat{\theta}_i < D_{\text{max}}^F \]

\[ W_i = W_{\text{max}}^F \text{ otherwise.} \]

(7.18)

If there is a problem of capacity with available stands for arriving aircraft, some stands must be freed as soon as possible, so that depending on arriving aircraft and on their stand assignment, the weight of the departing aircraft parking at these stands must be augmented as soon as possible to guarantee the availability of the stands for the arriving aircraft.
If $t_{ai}$ is the scheduled instant of parking of the next arriving aircraft to use the stand of the departing aircraft (i) and if current time (t) is such that: $t_{ai} - t < d_{\text{min}}$.

Then, whatever the class (size, passengers load, freight, ...) of the departing aircraft: $W_i^f = W_i \cdot \frac{d_{\text{min}}}{|t_{ai} - t|}$. (see Fig. 7.4)

Finally, if the planning horizon is much larger than the decision period ($T > > \tau$, $T$ at least 3 or 4 times $\tau$), a deflecting factor can be introduced to give a major weight to the next departing aircraft while a minor weight is given to late departing aircraft at periods for which the gap distribution may be updated:

Let the sequence $\rho_i$ be such that:

$$\rho_i = 1 \text{ if } i \in Q_k$$

$$\rho_i = 1 \text{ if } i \in A_k \text{ and } \Theta_i - t_{dk} < 2.\tau$$

$$\rho_i \leq 1 \text{ with } \rho_{i+1} \leq \rho_i \text{ for } \Theta_i - t_{dk} > 2.\tau$$

where $\Theta_{i+1} > \Theta_i$.

Then: $W_i^k = \rho_i \cdot W_i^k$

#### 7.6 The Real-time Decision Sequence

At time $t_{dk}$ a sequencing problem relative to departing aircraft over period $[t_{dk}, t_{dk} + T]$ is to be solved.

The real-time decision sequence is composed of the following steps:

- update of gaps available for departing aircraft,
- update of weights in the performance function ($P_k$),
- solution of the scheduling problem,
- realization of scheduled roll-out during period $[t_{dk}, t_{dk+1}]$. 

Page 124
Figure 7.4 Penalty for using stand (l).

\[ \tan \theta = \frac{W_i}{d_{\text{min}}} \]

\( W_i \)

\( t_{a_l - d_{\text{min}}} \)

\( t_{a_l} \)
The updating process for weights of $P_k$ has been already described in the former sub section. An updating process for gaps is necessary since, at time $t_{dk}$ predictions are never available for arriving aircraft and since departing aircraft leaving their stand during period $[t_{dk-1}, t_{dk}]$ may be reaching the runway during period $[t_{dk}, t_{dk+1}]$ see Fig. 7.5.

7.7 Definition of a candidate set of flights for a gap
Let $[t_B, t_E]$ be the gap considered and let $T(t_B)$ be the set of candidate aircraft for this gap. Flight (i) belongs to $T(t_B)$ if the following conditions are satisfied:

1) Flight (i) is not already assigned,

2) Minimum separation constraints are satisfied:
   - with preceding arriving aircraft, \( \varepsilon^{(ad)i} \)
   - with preceding departing aircraft, \( \varepsilon^{(dd)i} \)
   - with following arriving aircraft, \( \varepsilon^{(da)i} \)
   (see Fig.7.6)

3) Roll time constraints (velocity):
   \[ \tilde{\theta}_i \leq t_{Bi} - ts(i)v(i) \] \hspace{1cm} (7.20)

4) No ground conflict at roll-out:

Let $\beta (t_B)$ be the set of flights taking off before time $t_B$, we have the condition:

\[ \forall j \in \beta (t_B), t_{Bi} - ts(i)v(i) \geq \theta_j - \sigma \frac{v(i)v(j)}{s(i)s(j)} \] \hspace{1cm} (7.21)

where $\sigma \frac{v(i)v(j)}{s(i)s(j)}$ is the time buffer between aircraft leaving stands $s(i)$ and $s(j)$ with rolling speeds $v(i)$ and $v(j)$ see Fig. 7.7.

7.8 The Proposed Heuristic Decision Process (HDP)
The proposed (HDP) follows the considerations developed in the preceding chapter and avoids the combinatorial explosion of exact search methods
Figure 7.5 Real Time Decision Sequence.
Figure 7.6 Minimum Separation Constraints.
while guaranteeing an improvement over a basic up at hand solution. So this process is composed of two steps:

1) A basic solution is obtained from a greedy type procedure:

If \( T(t_B) = \emptyset \) consider the next time in the current gap such that, \( T(t_B) \neq \emptyset \), if this time doesn't exist go to the next gap.

If \( T(t_B) \neq \emptyset \) chose \( i \in T(t_B) \) such that (ordering process):

\[
W_i : ( t_{B_i} - \hat{\theta}_i - t_{s(i)v(i)} ) = \max \left[ W_j : ( t_{B_j} - \hat{\theta}_j - t_{s(j)v(j)} ) \right] \quad (7.22)
\]

So flight (i) will be scheduled to leave its stand at time \( \tilde{t}_{B_i} - t_{s(i)v(i)} \).

If the unused part of the current gap is sufficient to allow another departure, i.e.:

\[
t_E - ( \tilde{t}_{B_i} + \varepsilon_{a_{\text{min}}} ) \geq \varepsilon_{d_{\text{min}}} \quad (7.23)
\]

Where \( \varepsilon_{a_{\text{min}}} \) is the minimum runway separation with a following departing aircraft, while \( \varepsilon_{d_{\text{min}}} \) is the minimum runway separation of a departing aircraft with the aircraft landing at \( t_E \) see (Fig. 7.8).

Then a new gap starting at time \( t_{B_i+1} = \tilde{t}_{B_i} + \varepsilon_{a_{\text{min}}} \) and ending at time is considered to be the next gap for departing aircraft.

This process is repeated until every aircraft in \( A_k \cup Q_k \) has been assigned a roll-out time from its stand.

The performance of this scheduling is then:

\[
\tilde{P}_k = \sum_{i \in A_k \cup Q_k} W_i \cdot ( \tilde{t}_{B_i} - \hat{\theta}_i - t_{s(i)v(i)} ) \quad (7.24)
\]

### 7.9 Improvement of the Basic Solution

The decisions taken at time \( t_{d_k} \) which cannot be updated at decision time \( t_{d_k+1} \) are those which concern stand departures between \( t_{d_k} \) and \( t_{d_k+1} \) (see Fig. 7.5). Thus particular care must be taken for this class of departures.
Figure 7.7 Non conflicting rolling out manoeuvres.
Figure 7.8 Gap update condition.
If \( n \) flights are assigned to leave their stands during this period with the basic solution, it must be assumed that in the optional solution at least \( n \) flights will be leaving their stands. So there will be at least \( n! \) solutions to be considered. For instance for \( n=7 \) there will be more than 5000 partial solutions to be considered.

The proposed improvement is as follows:

Let \( N \) be an integer such \( 0 < N \leq n \) and let \( M \) be another integer such that \( 0 < M \leq N \).

Consider the first gap such that \( T(t_B) \neq \emptyset \) for \( t_d k \) and generate the following solutions see (Fig. 7.9).

Where \( 1 \leq i_k \leq M \), \( K=\{1,...,M\} \) and \( f(i_k) \) being the \( i_k^{th} \) solution of the ordering process used in the greedy procedure of the basic solution at its \( k^{th} \) step (the \( k^{th} \) departure). After the \( N^{th} \) departure, the greedy procedure is adopted (the first flight is always retained) and for each solution its performance is computed.

There are no more than \( M^N \) solutions to be considered here since some shifting may be unfeasible (a stand \( i \) must be freed before time \( t_{a_i} \)).

Let \( \left[ f(i_1^*), f(i_2^*), ..., f(i_N^*), f(1), f(1), f(1), ..., f(1) \right] \) be the best local solution (its performance index, relation (7.10), is minimum over the \( M^N \) solutions), then flight \( f(i_1^*) \) will be definitively retained if this solution is better than the following gap (resulting from the former decision) and is repeated until the chosen flight leaves its stand after time \( t_{d_{k+1}} \).

So we get a solution which is at least no worse than the basic solution after a computation effort which can be controlled by an adequate selection of parameters \( M \) and \( N \).
Figure 7.9  Local Optimum ordering of flight.
Example:
Suppose we have the results with $t_{dk} = 0$, $t_{dk+1} = 600s$, $N=3$, $M=2$ see (Fig. 7.10).

Here also the second best flight is chosen to occupy the second departure position at the runway.

This process is repeated until $\theta_i^* > t_{dk+1}$, where $\theta_i^*$ is the leaving time of the last chosen departure, this last departure time will be reconsidered at decision time $t_{dk+1}$.

7.10 Estimation of the number of solutions to be considered

Consider Fig. 7.11:

Let $l_i$ be the length of gap (i) contained in the interval $T_k = [t_{dk} + \frac{d_{\text{min}}}{v_{\text{max}}}, t_{dk+1} + \frac{d_{\text{max}}}{v_{\text{min}}}]$, let $E_{\text{min}}$ be a minorant of every kind of minimum separation time at the runway, the max number of departing aircraft $D_{\text{min}}$ during period $[t_{dk}, t_{dk+1}]$ is given by:

$$D_{\text{max}} = \min \{ D_k, D_s \}$$

(7.25)

with

$$D_k = \text{Card} \left( Q_k \cup \{ i \in A_k, t_{dk} < \theta_i^* \leq t_{dk+1} \} \right)$$

and

$$D_s = \sum_{s_i \in S_k} \left\lfloor \frac{l_i}{E_{\text{min}}} \right\rfloor$$

(7.26)

where

$$S_k = \{ \text{gap } s_i \mid s_i \subseteq T_k \}$$

and $[x] = \text{integer part of } x$.

So the maximum number of solutions to be considered is given by:

$$N_{\text{max}} = M^N \cdot D_{\text{max}}$$

Example: $M = 2, N = 2, D_{\text{max}} = 5$: $N_{\text{max}} = 20$

$M = 2, N = 3, D_{\text{max}} = 10$: $N_{\text{max}} = 80$
1° Step:

\[
\begin{align*}
1 & \quad 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 2 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 2 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 2 & 2 & 1 & 1 & 1 & 1 & 1 & 1 \\
2 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
2 & 1 & 2 & 1 & 1 & 1 & 1 & 1 & 1 \\
2 & 2 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
2 & 2 & 2 & 1 & 1 & 1 & 1 & 1 & 1 \\
2 & 2 & 2 & 2 & 1 & 1 & 1 & 1 & 1
\end{align*}
\]

\[
\begin{array}{c}
18650 \\
18920 \\
20850 \\
21020 \\
17860 \\
17980 \\
19040 \\
19840
\end{array}
\]

Basic Solution

The second best flight is chosen to occupy the first position in the first slot.

2° Step:

\[
\begin{align*}
2 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
2 & 1 & 1 & 2 & 1 & 1 & 1 & 1 & 1 \\
2 & 1 & 2 & 1 & 1 & 1 & 1 & 1 & 1 \\
2 & 1 & 2 & 2 & 1 & 1 & 1 & 1 & 1 \\
2 & 2 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
2 & 2 & 1 & 2 & 1 & 1 & 1 & 1 & 1 \\
2 & 2 & 2 & 1 & 1 & 1 & 1 & 1 & 1 \\
2 & 2 & 2 & 2 & 1 & 1 & 1 & 1 & 1 \\
2 & 2 & 2 & 2 & 1 & 1 & 1 & 1 & 1
\end{align*}
\]

\[
\begin{array}{c}
17860 \\
18020 \\
18320 \\
17540 \\
17200 \\
17280 \\
18310 \\
18420
\end{array}
\]

Figure 7.10  Example of Searching for the Best Solution.
Example related to different stand distances and taxi speed.

Figure 7.11  An Example of general airfield configuration.
\[ M = 3, N = 3, D_{\text{max}} = 10: N_{\text{max}} = 270 \]
\[ M = 3, N = 4, D_{\text{max}} = 10: N_{\text{max}} = 810 \]

### 7.11 Concluding Remarks

In this chapter, we have proposed an heuristic approach for the real time scheduling problem of departing aircraft. This approach has four main advantages:

- it can be easily understood by managers,
- its computational burden is controllable,
- it offers a solution procedure which can be easily implemented in a digital computer for on-line control,
- the procedure can be re-started after any disruption in the flow of inbound or and outbound aircraft.

Its major difficulty is in the choice of the weights associated, in real time, with each departing flight. This choice is complex since it has political, economical and technical implications for the airlines, the airport authorities and the users. Adequate choices should be made to guarantee not only equity between airlines but also an efficient use of the available runway capacity. The results of this study can inform the lengthy and difficult debate which will needed to resolve this issue.

Here it seems possible to use expert knowledge, obtained from practical experience and simulation studies, to choose these weights. In general expert systems are good this kind of decision, even in real time, provided they an adequate knowledge base. The building of such a knowledge base could be conducted in the light of recent experiments in other fields of transportation engineering. Then in normal operation the whole decision process should take advantage of the right choice of current weights for the decision function. In the case of compute failure, the human supervisor should be able to take control of the on-line scheduling activity, without any delay.
CHAPTER EIGHT

Implementation and Computational Results

8.1 Introduction
This chapter displays the preliminary application of the heuristic scheduling algorithm proposed in chapter 7 for the management of departing aircraft at a generic airport.

A PC compatible computer code, named SAIDA, has been developed in Turbo-Pascal to be run in PC compatible computers. This code allows the comparison of a First Come First Served (FCFS) policy with the proposed heuristic and the analysis of the influence of different design and situation parameters such as:

- level of inbound and outbound aircraft flows,
- mix of aircraft classes,
- distribution of delay-free taxiing and roll-out times,
- length of the decision time window,
- distribution of weights in the decision criterion, over the performance of the method.

8.2 Basic Assumptions for Analysis.
We consider an airport with a single runway and a variable level of demand spread over a given period of time (from 5 a.m. to 9 a.m.).

Demand levels have been taken from 10 to 40 movements/hour (50% arrival and 50% departure) during the above period of time, the latter value being the capacity level for the runway. The length of the decision time window has been chosen between 10 minutes and 40 minutes.

Planned arrival times and desired departure times can be generated by a random process over the given period of operation or can be obtained from
predefined time tables. Arrival runway occupancy times, taxi times either inbound or outbound, departure runway occupancy times are defined by random processes from given probability distributions. In general, normal distributions with tenable variances have been used. To each departing aircraft is assigned a weight ranging from 1 to 10. This weight must integrate the size of the aircraft, its cargo (passengers or/and goods) and its strategic importance (scale of priorities) so that any delay in its effective departure can be related to its real importance to the airport authority. The desired departure time tables may be related with a slot allocation process by the consideration of nominal departure delays.

The decision criteria chosen in this case is a quadratic form such as:

\[ DC = \sum_i \text{weight}(i) \cdot (\text{delay}(i))^2 \]

where \( i \) is an index over the remaining aircraft candidates to departure. This form implies a higher penalty for aircraft suffering already a high delay so that they gain an increased priority which is proportional both to their weight and to the square of their current delay.

In this study no constraint has been considered regarding parking conflicts. However, it should be easy to introduce this aspect by increasing the penalty of the departing aircraft which occupies the parking stand assigned to an arriving aircraft.

In the case where flexible assignment of parking stands for arriving aircraft is possible, the scheduled departure time of aircraft from their parking stand will be a fundamental input to the on line assignment problem of parking stands to arriving aircraft. One of the main objectives of this auxiliary decision problem will be to minimize or even to cancel any conflicts within the taxiway sub system. Two attitudes can be adopted:

- 1) To tackle them through the use of priority rules. In this case, queuing delays at intersections, with engines on, may appear. However since these delays can be foreseen and appraised, another attitude may be considered.
2) To avoid them by imposing additional waiting times at the parking stand with engines off. This is the approach chosen in this work.

The delay measures of interest here are:

- **total weighed delay**  
  \[ TWD = \sum_{i} \text{weight}(i) \cdot (\text{delay}(i))^2 \]
  
  where \( i \) is an index over the whole set of departing aircraft during the period of operation considered and \( \text{delay}(i) \) is the effective delay imposed (at parking stand) on departing aircraft \( i \).

- **mean weighed delay**  
  \[ MWD = \frac{TWD}{NDA} \]
  
  where \( NDA \) is the number of departing aircraft during the period.

Minimum delay:  
\[ D_{\text{min}} = \min_{i=1 \text{to} NDA} \left[ \text{weight}(i) \cdot \text{delay}(i) \right] \]

Maximum delay:  
\[ D_{\text{max}} = \max_{i=1 \text{to} NDA} \left[ \text{weight}(i) \cdot \text{delay}(i) \right] \]

These measures allow a complete assessment of the quality of the solution provided by the proposed heuristic method since in theory it provides a scheduling for departures free of queuing delays with engines on if taxiing conflicts have been avoided. It is not the case with a First Come First Served strategy where queueing delays may appear at the proximity of the runway control point.

### 8.3 The Program Structure

In this section an overview of the program structure is presented, see Figure 8.1. The details of the code are displayed in Appendix 5.

Part I of the code is devoted to initializations and FCFS policy evaluation:

According to means of flows for arriving and departure aircraft, timetables for the arrivals touch down at the runway and desired departures from the parking stands are generated. Periods of occupancy of the runway are computed according to the class of the inbound aircraft so that time gaps at the runway are available.
Definition of Problem: Time Period Total Flows

Random Pre-planned

Arrivals

Random Generation of Arrivals Entrance of Arrival Time Table

Calculation of Gaps at Runway

Random Pre-planned

Departures

Random Generation of desired departure times Entrance of Desired Departure Time Table

FCFS Schedule of Departing Aircrafts

Calculation of Delays and Fuel Consumption with FCFS Policy

Figure 8.1.(a) The Program Structure (Part I)
New Time Window

Estimation of Current Queue and Penalties for Candidate Aircraft

Choice of current Schedule During Time Period With Use of the procedure Monitor, Scrabble and Select

Update of Delays and Queues

yes

New Time Window?

no

Calculation of Scheduled Departures and Delays

Display of Final Results

Figure 8.1.(b) The Program Structure (Part II)
Then the string of outbound flights is processed: according to their position in the desired departure time-table, aircraft are treated by the FCFS policy, i.e. aircraft are cleared on schedule and directed to the runway threshold. Since the geometry of the taxiways in the airfield has not been defined, conflicts at this level are not taken into consideration. Conflicts at the runway threshold are of main concern here, they are the result of the arrival of departing aircraft at a queue generated by a leading aircraft which waits for the clearance of the runway for take-off under minimum separation rules. In this study only time dependent minimal separation standards have been used.

For the generation of arrival separation at the runway (final approach), the wake vortex spacing minima for arrivals where considered, see Table 8.1. For departures separation (take-off), the departure track separation criteria, see Table 4.1, and wake vortex spacing minima for departures (Table 8.2) were used.

In the case where departing aircraft diverging by more than 45 degrees, a one minute separation is assigned to the value these minimum separation.

Once every departing aircraft over the whole period considered has been assigned a rolling-out time for take-off, delays and fuel consumption levels are calculated according to the indexes proposed in the preceding section. A mean fuel rate is considered for each class of aircraft, chemical pollution is assumed to be proportional to total fuel consumption and thus is not explicitly calculated.

The second part (Part II) of the code is directly concerned with the operation and the evaluation of the heuristic solution algorithm:

A large time loop corresponds to the scanning of the whole period of operation through a time window of pre-fixed length and this in a recursive way.

Once the time window has been positioned, the current operational situation is appraised: delayed aircraft at their stands, scheduled aircraft for the current and the next time window. Following the principles described in the
<table>
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<tr>
<th></th>
<th>J</th>
<th>Heavy</th>
<th>Medium</th>
<th>Small</th>
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<td></td>
<td>Light</td>
<td>-</td>
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</tbody>
</table>

(i) - Leading Aircraft
(j) - Following Aircraft

Wake Vortex Spacing
Minima - Final Approach
(U.K. Standard)

Table 8-1 Minimum inter-arrival times (tij in seconds).
<table>
<thead>
<tr>
<th>Leading Aircraft</th>
<th>Following Aircraft</th>
<th>Minimum Spacing at the Time aircraft are Airborne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>Medium / Small or Light Departing the same position</td>
<td>120 seconds</td>
</tr>
<tr>
<td>Medium or Small</td>
<td>Light Departing the same position</td>
<td>120 seconds</td>
</tr>
<tr>
<td>Heavy (Full length take-off)</td>
<td>Medium / Small or Light Departing the intermediate part of the same runway</td>
<td>180 seconds</td>
</tr>
<tr>
<td>Medium or Small (Full length Take-off)</td>
<td>Light Departing the intermediate part of the same runway</td>
<td>180 seconds</td>
</tr>
</tbody>
</table>

Ref. U.K. Aeronautical Information Circulars C.A.A.

Table 8-2 Minimum inter-departure times (tij in seconds).
preceding chapter, procedure **Weight** updates the weight of each candidate aircraft for departure (delayed and scheduled ones).

Then a set of tentative schedules is established by procedure **Monitor** with a filter technique, then procedure **Scrabble** picks them up, memorizes intermediate data and submits them to the **Select** procedure which chose the best local schedule.

In fact, procedure **Monitor** selects only feasible schedules and procedure **Scrabble** orders these candidate schedules starting from the FCFS schedule and proceeds by substitutions. The **Select** procedure makes uses as decision criterion the total weighed delay (TWD) calculated over the set of remaining candidate flights for the current time window.

Again, once every departing aircraft has been assigned a clearance time from stands, delays and fuel consumptions indexes are calculated.

Finally, comparative results are displayed between the FCFS policy and the proposed solution approach (heuristic).

To get results with a statistical meaning, an outer loop can be added to the whole linear calculation structure to generate a set of random samples either at departure and arrival times as at taxiing, roll in and roll out times. Then means and standard deviations can be calculated for delays and fuel consumptions.

### 8.4 Numerical Results

Program SAIDA has been run extensively to assess the proposed decision algorithm and to achieve a sensitivity analysis with respect to its main design parameters.

First in Figure 8.2 we present the evolution of mean delays when departing flows vary from 10 movements/hour to 40 movements/hour while departures are managed under the proposed decision algorithm. In this case the decision time window is taken equal to half an hour which is by actual standards a maximum value and the mix of aircraft classes is taken even (25% each).
Figure 8-2  Evolution of mean delays from proposed Heuristic Methodology.
It is noticeable that the mean delays curve has two discontinuities at 15 movements/hour and at 30 movements/hour.

So, after 15 movements/hour, departure movements are affected by traffic congestion, while beyond 30 movements/hour the system becomes saturated. At saturation, around 40 movements/hour the mean delay is over 33 minutes. These values can be compared with those measured at major airports. For instance in the case of Gatwick Airport, total delay which includes initial delay and holding point delay, exceeds 40 minutes in similar conditions.

In Figure 8.3 the evolution of the standard deviation of the mean delay is presented with respect to the volume of ground movements.

Thus it is possible to see that the relative dispersion of delays diminishes with increasing flows. This phenomenon can be explained not only by the saturation which affects every flight when it reaches high levels, but also by the nature of the decision algorithm which in the mean tends to follow an equity principle by avoiding too large delays for particular flights.

In Figure 8.4 the influence of the duration of the decision time window (DTW) is shown over the performance of the proposed heuristic. There, an average of 30 movements/hour is adopted, while the mean delay free taxiing time is chosen equal to 420 seconds and the traffic mix is: H=40%, M=25%, S=25%, and L=10%.

Thus, the duration of DTW is seen as being a design parameter which has an important influence over the performance of the proposed algorithm. The greater the DTW, the smaller the average delay. However, beyond 30 minutes, it is noted that no more improvements are gained, thus the average delay appears to comply to a decreasing returns law. When the time window is comparable to the maximum delay-free taxiing time, the algorithm cannot take advantage of gap predictions and the scheduling is blind and lead to bad performance. In Figure 8.5, the same analysis is performed with a lower traffic (20 movements/hour).

In Figure 8.5 it appears that the sensitivity of the performance to the duration of DTW increases (decreases) with increasing (decreasing) traffic.
\[
\frac{SD}{AD} = 0.50 \quad 0.478 \quad 0.448 \quad 0.408 \quad 0.366 \quad 0.342 \quad 0.340
\]  
(Relative value)

\[SD = \text{Standard deviation} \quad \text{and} \quad AD = \text{Average delay}\]

Figure 8-3  Mean delay standard deviation evolution with traffic.
Figure 8-4  Influence of the duration of the decision time window.

(30 movements / hour)
Figure 8-5  Average delays influence of DTW duration.

(20 movements / hour)
This can be well understood since in a heavier traffic situation more flights compete for the same time period and a wider DTW allows the consideration of a larger number of possible reordering and gives way to an improved schedule selection. However it seems that this result depends also on the mix of aircraft considered in departing traffic.

In Figure 8.6 the influence of the mean duration of taxiing, while the duration of the DTW is taken equal to 20 minutes, is observed. Here also it is noted that the proposed scheduling algorithm loses its efficiency when taxiing duration becomes equivalent to the one of the DTW. However in a large interval, the average performance is not affected by this parameter.

8.5 Comparison with a FCFS policy
In Figure 8.7 the traffic conditions of figure 8.2 are considered and the performance of a FCFS policy for departure scheduling is reported for comparison with the heuristic algorithm.

Thus we see that until 33 movements / hour the heuristic technique provides smaller mean delays for departing aircraft by approximately 7%.

We note also that beyond 33 movements / hour the extra delay for FCFS remains approximately constant, decreasing in percentage terms. This means that the relative efficiency of the heuristic algorithm over the FCFS policy decreases.

The influence of the mix of traffic has been considered when the level of activity is of 20 movements/hour (DTW equal to 30 minutes). Three traffic mixes have been considered:

1) H=25%, M=25%, L=25%, S=25%;

2) H=50%, M=0%, L=0%, S=50%;

3) H=0%, M=100%, L=0%, S=0%.

The heuristic approach provides an improvement over the FCFS policy of 11% in the first case, 12% in the second case and only 8% when only class M aircraft are present. This result can be clearly understood, since non uniform traffic provides many more opportunities to find improved reor-
Figure 8-6. Influence of taxiing duration (30 movements/hour).
Figure 8-7 Mean delays resulting from FCFS and Heuristic schedules.
dering than an uniform traffic where only current or potential delays will affect the choice of a schedule.

The improvement of the system performance through the use of the proposed heuristic algorithm seems at first sight modest. However a fundamental difference exists between delays generated by the FCFS technique and the heuristic technique:

- FCFS delays are engines on delays and measure not only time delays for passengers, crews and airport managements, but also fuel consumption, pollutant emission and noise generation levels.

One could ask if it is not possible, by inversion, to get from a FCFS schedule a departure schedule free of delays with engines on, by postponing the departure time of a duration equal to the queuing delay. In fact this operation is not possible since a complete prevision of gaps for the entire period considered is not available at its first instant. So in general, the heuristic technique provides an on-line scheduling which is much more efficient than the FCFS rule.

In Figure 8.8 relative fuel costs are reproduced, the traffic conditions being those considered in figure 8.7.

Thus it appears here that the proposed heuristic algorithm has the potential to save large quantities of fuel and to avoid the emission of large amounts of pollutants.

In what follows, schedules resulting from FCFS policy and the proposed heuristic are compared in detail. A traffic of 30 movements/hour is considered with a mix given by: H=50%, M=10%, L=10%, S=30%.

The SAIDA program provides through the use of random generators timetables for inbound flights and computes runway gaps (see Table 8.3).

In table 8.4 are displayed the initial weight assigned to the 60 departing aircraft.

The SAIDA program computes then from desired departure times the effective departure times of each outbound flight. These results are dis-
Figure 8-8 Comparison of Fuel cost resulting from FCFS and Heuristic schedules.
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<th>End time</th>
<th>Gap</th>
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Table 8-3  Gaps distribution at the runway.
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Table 8-4(a)  Initial weights for departing aircraft.
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Table 8-4(b) Initial weights for departing aircraft.
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Table 8-5(a)  Desired and effective departure time  (Heuristic).
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<td>60</td>
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</table>

Table 8-5(b) Desired and effective departure time (Heuristic).
played in Table 8.5. Finally, delays resulting from the FCFS policy and the heuristic algorithm are displayed in Table 8.6 for each aircraft taken individually.

Consider in Table 8.6 aircraft number 10, 11 and 12 respectively. Their desired departure times are close and so they are competitors for runway gaps. However, it is noted that their weights are respectively 3, 10 and 10.

It is seen that the heuristic algorithm rejects the FCFS ordering so that the delay of aircraft with higher weights (11 and 12) is minimised while the delay of the aircraft with the lower weight is maximised. In this case the weighted gain with this local reordering is:

\[ 10 \left( 149 - 89 \right) + 10 \left( 89 - 29 \right) - 3 \left( 149 - 29 \right) = 840 > 0 \]

Note also that here the total net gain in time delay, regardless of the weight or the class of aircraft is null and that the delay diminution is the same for the two aircraft having the same weight. This can be explained by the fact that 30 movement/hour is already a rather high level of activity and that in this example, locally there is no more room in the runway gap to be taken into profit.

8.6 Treatment of perturbations

Until now, nominal conditions have been assumed, while many perturbations may happen and make difficult the realization of the ideal scheduling generated by the heuristic method. Three main sources of perturbation may be pointed out:

- imprecision in the prediction of touchdown time by arriving aircraft. This inaccuracy may be diminished by the use of new 4D guidance systems over periods of time of duration below half an hour. Note that this inaccuracy is expected to increase with the level of demand.

- inaccuracy in taxiing speeds and durations.

- additional delays at beginning of push back or engine start caused by unavailable handling equipment or communication and control difficulties.
<table>
<thead>
<tr>
<th>Aircraft Number</th>
<th>Delay (FCFS)</th>
<th>Delay (Heuristic)</th>
</tr>
</thead>
<tbody>
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<td>209</td>
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<tr>
<td>2</td>
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Table 8-6(a)  Delay from FCFS and Heuristic Techniques.
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Table 8-6(b) Delays from FCFS and Heuristic Techniques.
To limit the influence of these inaccuracies over the performance of the proposed method, diverse solutions are possible, including regulation of taxiing speeds in order to absorb an additional delay or eventual lead.

Let (l) be a taxiing distance, at nominal speed (v) it takes (l/v) seconds to perform it. The taxi delay may then be regulated from the apron within limits: (l/v_max) and (l/v_min). If speed regulation is activated at a distance (L) from the runway threshold, these limits reduce to (L/v_max) and (L/v_min) so that the ability to absorb a delay or a lead reduces with the distance already covered from the parking stands. It appears also interesting to predict any modification about the departure slot of an aircraft before it leaves its stand. In general taxi times are far less than the actual prediction window for departure gaps, so that a speed regulation policy seems sufficient to compensate limited delays and leads at the runway. Note that such a regulation policy will imply added fuel cost which however should remain limited in relation with fuel costs resulting from FCFS like policies:

- the use of a FCFS policy for a limited period of time necessary to get rid of a queue of arriving aircraft at the runway threshold. The heuristic approach is recovered as soon as the queue is over. Note that the proposed approach can be corrected to include this process of reduction of perturbation queues. Here also this solution has a positive but limited influence over fuel expenditure.

- Also some penalty schemes may be enforced for aircraft which do not follow the proposed time-schedule: loss of turn in the departing sequence, added waiting times either at the stand or at a hold point until a new departure slot is allocated to it in a new scheduling round.
CHAPTER NINE

CONCLUSIONS

The research investigation, which forms the subject of this discussion, was directed to the design of an efficient scheme for the management, in the short run, of departing aircraft at major airports where congestion phenomena occur frequently both in the near airspace and at the airfield.

9.1 Position of the Research

All around the world, air travel delays have become a major problem, because aircraft traffic demand are overtaking the current operational capacity of major airports. Environment and cost considerations have restricted both the expansion of existing airports and the building of new terminals. Consequently, considerable efforts are at the present time directed at enhancing the capacity of existing terminals. One of the major challenges is to determine how best to take advantage of advances in communication data processing and control technology:

- Mode S data communication channel, Microwave landing Systems, powerful processors based on Transputer technology, Expert Systems and Neural Nets in the field of artificial Intelligence.

One of the outcomes of advanced avionic research has been the development of aircraft 4-D flight Management Systems which allows the efficient guidance of aircraft to a given runway at a designated time.

Thus the operation of en route arrival metering techniques and of computer - aided terminal sequencing and spacing systems give way to accurate predictions of runway occupancy times which are available with enough antecedence so that new ground traffic management techniques can be operated.
So, the concept of Total Automation of Air Transportation Operations becomes a reality and the present study constitutes a contribution to this objective.

The problem considered in this research work stands at the operations level. It is related in one side with planning activities devoted to departures: capacity management of the airfield and in a shorter horizon, slot negotiation and allocation.

On the other side, this problem is related with other problems standing at the operations level:

- terminal air traffic control, Ground traffic control, parking stands allocation for inbound aircraft, ground operations at stand.

This constitutes then an intricate network of connections and interrelationships which make the detailed delimitation of the problem extremely complex and raise difficulties for the assessment of consequences resulting from the automation of this sector over adjacent sectors of operations.

The main objectives pursued with the automation of departures are:

- **safety**: this is a permanent concern in the Air Transport field where safety has been the primary objective and a basic "sine qua non" condition of feasibility for this mode of transportation. At the ground level this objective is met by the satisfactory resolution of traffic conflicts at taxiways and manoeuvre areas and by the enforcement of minimum separation standards at the runways.

- **reliability**: computer and communication technology have gained today high degrees of integrity and the use of these devices for automation of departures will constitute an easing of workload for the ground traffic control team whose position becomes one of supervisor and no longer of direct control actor.

- **efficiency**: One of the main advantages of using automation is the possibility to develop complex calculations to detect what is the more efficient decision at each decision time for a whole period of operation.
The development of such a scheme is the principal goal of the present research work. The expected consequences are:

- reduction of the incidence of delays at departure for passengers and airlines,
- reduction of fuel consumption by aircraft achieving delay-free departures with engines on,
- reduction of pollutant emission directly related with fuel consumption,
- reduction of noise around airports and their neighbourhood.

9.2 Major Findings

The first part of this manuscript introduces the necessary elements for the identification and delimitation of the problem under study. The major contributions of this research work are then displayed in the second part of this manuscript.

In Chapter Six, a mathematical programming approach of the departure scheduling problem is performed and an original decision model is formulated in mathematical terms. This new decision model includes a quantitative objective function, which is quite understandable by managers, and operations constraints of real time nature in general. The intractability of this decision problem through the use of exact solution algorithms is recognized:

- complete enumerative solutions imply a response time for the calculation devices which is not compatible with real time applications,
- many data are unavailable at current time and is replaced by predicted values which may be further updated and thus damage the performance of the system.

Two approaches to a solution are nevertheless pointed out:

- Heuristic methods and Knowledge Based-(KB) methods.
The main advantage of KB methods, which have recently been considered with some interest by researchers in the field of transportation engineering, is the ability to take into account qualitative knowledge. However their main disadvantage is to provide solutions through a process (Artificial Intelligence Techniques) which remains esoteric and brings no degree of confidence to the traffic manager who should supervise the process.

This is not the case with Heuristic Methods whose logic is in general built up from practical knowledge. The Heuristic approach has then been recommended for the solution of the scheduling of departures.

In Chapter Seven it is proposed an original heuristic solution for the problem under study. The design of the solution approach is carefully detailed and discussed with the objective of guaranteeing its effectiveness. In particular, criteria are developed for the selection of the main design parameters:

- decision horizon length, index of performance with time borders, sampling period for decision making, search technique.

The whole solution approach is designed such that its performance cannot be worse in term of delay than a well known technique, the First Come First Served procedure, taken as reference.

The design and the updating process of weights assigned to each aircraft in the decision criteria are given a solution which makes the whole solution method quite understandable by human supervisors.

Also the search technique is carefully conceived to realize a satisfactory trade off between solution accuracy and calculation volume (computer response time).

A computer program, named SAIDA, has been developed to make preliminary tests of the proposed Heuristic algorithm. This program considers departures at a generic airport operating a single runway.

Chapter Eight displays the main results of a sensitivity analysis study performed using SAIDA: a decreasing returns effect is detected with respect to the duration of the decision time window used in the scheduling
process while the influence of taxiing distances and mix of traffic over delays is assessed. Then a **comparative study** with respect to the FCFS technique is performed. The proposed heuristic algorithm appears to be always superior to this technique although the relative gain in delays varies from 0% to 15% under different conditions of traffic and of tuning of the design parameters of the solution algorithm. This simulation study shows also that this method has the **potential to save large quantities of fuel and to minimise pollutant emission** during aircraft departures.

### 9.3 Recommendations for further work

In this research investigation, a number of suggestions for further work have been identified.

- 1) The heuristic algorithm may be extended easily to cope with traffic conflicts at taxiways and airways. In this case the monitoring procedure of SAIDA must be completed to incorporate these new class of conflicts and associated restrictions.

- 2) Since field experiments to validate and assess the proposed solution technique cannot be considered without much more detailed and extensive studies involving airline, airport and governmental authorities, a more accurate simulation study than the one presented in this manuscript must be conducted. One way could be to construct a departure scheduling module which incorporates the heuristic algorithm and which should be appended to an airport simulation package such as SIMMOD. Then real size simulation studies of the performance of the proposed method could be performed allowing its analysis in the presence of transits and saturations.

- 3) The heuristic algorithm has been designed to cope with single operated runway airports. A research study seems necessary to find out how to extend its applicability to the case of various runways and terminals. Depending on the structure of the airfield, decomposition and co-ordination principles should be established to deal with this increased complexity. In this case techniques such as real time Petri Nets and other tools from Graph Theory should be used.
4) Another important work which should be performed to ensure the applicability of the proposed approach is to study its consequences for the work practice of the airport traffic controller team. In particular, their new position as supervisors of an automated departure scheduler should be defined in details. Also, new needs in information (communication channels and electronic displays) should be determined and related with the main objectives of security, reliability and efficiency of ground operations at airports.
REFERENCES


Civil Aviation Authority, "Aeronautical Information Service", AIS 1c 90/1986.

Civil Aviation Authority, "Gatwick Monitoring Summer 1987".

Civil Aviation Authority, "Gatwick Monitoring Summer 1989".

Civil Aviation Authority, "Rules for Air Traffic Control".


Joline, E. S. (1974) "Optimisation of runway exit configurations", Transportation Engineering Journal, Volume 100, No. TE1, February 1974, p85-102, American Society of Civil Engineers, USA.


BIBLIOGRAPHY


Boeing AIRLINER. " Fuel Conservation Newsletter ". No.9, January - March 1983.


Champniss G. A., "Air traffic management - The impact at the airport." British Airports Authority.


Civil Aviation Authority, "Runway capacity and aircraft delays at Gatwick airport ", CAA paper 8002, U.K, 1981.


Enhanced automated terminal control system is installed at Leningrad", Aviation Week & Space Technology v124, p154-5, 13 January 1986.


Federal Aviation Administration, (1983), "Airport Capacity and Delay", Advisory Circular No. 150/5060-5, USA.


Harris, R.M. (1972) "Models for runway capacity analysis", Report No. FAA-EM-73-5, Federal Aviation Administration, USA.


Hockaday, S.L., "Operation means for increasing runway capacity", paper in Airfield and Airspace Capacity and Delay: Problems and Action Areas,
Transportation Research Circular No. 286, p7-11, Transportation Research Board, USA, 1984.


Houghton, E.L. Brock, A.E. "Aerodynamic for Engineering students".


Performance Volume 6: Reduction and Estimation. ESDU Aeronautical Series.


Report of the working party on traffic and capacity at Heathrow, Department of Trade and Industry, CAP 349 - 1971.

Runway Capacity and Airport Delay at Gatwick Airport. CAA Paper 81002, January 1981.


APPENDIX 1

DATA ACQUISITION

1 Introduction
During the development of the Heuristic program, specific data requirements were identified. Therefore it was essential to carry out field study at typical busy airport to collect information on aircraft movements during the different phases associated with arrivals and departures and on ATC spacing between aircraft operations. The field studies took place at Gatwick airport.

Arrivals and departures (ref. Gatwick Monitoring) were monitored by DORA on:
- Monday 27 July 1987,
- Saturday 15 August 1987,
- Saturday 22 August 1987,
- Monday 24 August 1987,
- Friday 26 May 1989
- Friday 23 June 1989,
- Friday 21 July 1989, and
- Friday 22 September 1989.
(Data were collected on runways 26L and 08R during busy hours in the morning, between 0600 to 1300 UTC).

The time at which an aircraft begins or completes a manoeuvre was recorded. Then the duration of each manoeuvre as well as the spacing between successive operations was found the proper time differences.
2 Landing aircraft:
For landing aircraft, the following observations were made:

- Aircraft type,
- Time at end of runway,
- Time at threshold,
- Time to clear of runway,
- Turn-off block,
- Weather,
- Scheduled time

See Table 1 for reference.

3 Departing aircraft:
For departing aircraft the following observations were made:

- Original DFR slot,
- Given push-back time,
- Given taxi time,
- Time at holding point,
- Time aircraft line-up,
- Time aircraft starts to roll,
- Time airborne,
- Scheduled time.

Information from CAA Gatwick Monitoring tape see Tab.1 for reference.
Table 1: Arrivals and Departures monitoring at Gatwick Airport

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<td>11:00</td>
<td>Flight G</td>
<td>Flight H</td>
</tr>
</tbody>
</table>

Note: Times are in 24-hour format.
4 Arrival Data Analysis
The analysis performed on the data provided the following results:

4.1 Inter-arrival separations
The relative percentage of the four aircraft categories during the observation periods is presented in the table 2. For this traffic mix, the spacing (in seconds) between arrivals was as shown in table 3.

4.2 Runway Occupancy time
The number of observations for the runway occupancy time (ROT) were 202 for runway 26L at summer 1989, split according to the mix presented at Table 4.

5 Departure Data
The relative percentage of the four aircraft categories during the observation periods is presented in the Table 5. For this traffic mix, the spacing (in seconds) between departures was as shown in table 4.

5.1 Taxi out time.
The taxi time from stand to the holding point near the runway is represented by the difference between time at holding point minus "given taxi time" from table 1.

5.2 Take-off roll times
The Table 6 provides results (time in seconds) for take-off roll for the four type of aircraft (summer 1989).

5.2 Departure Separations
Departing aircraft are separated according to the routes they fly (same route or different route), their speed characteristics and their wake vortex categories (Annex 3).

At Gatwick in 1989 there were 3 recognised routes for runway 26L and 4 recognised route for 08R. See Table 7.
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<tr>
<td>22 August 1987</td>
<td>28.4</td>
<td>58.9</td>
<td>2.1</td>
<td>10.5</td>
<td>95</td>
</tr>
<tr>
<td>24 August 1987</td>
<td>27.3</td>
<td>50.9</td>
<td>6.4</td>
<td>15.5</td>
<td>110</td>
</tr>
<tr>
<td>Total Period</td>
<td>27.5</td>
<td>56.3</td>
<td>3.7</td>
<td>12.5</td>
<td>397</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Date</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>No. of Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 July 1987</td>
<td>5.2</td>
<td>12.5</td>
<td>96</td>
</tr>
<tr>
<td>15 August 1987</td>
<td>1.0</td>
<td>11.5</td>
<td>96</td>
</tr>
<tr>
<td>22 August 1987</td>
<td>2.1</td>
<td>10.5</td>
<td>95</td>
</tr>
<tr>
<td>24 August 1987</td>
<td>6.4</td>
<td>15.5</td>
<td>110</td>
</tr>
<tr>
<td>Total Period</td>
<td>3.7</td>
<td>12.5</td>
<td>397</td>
</tr>
</tbody>
</table>

Table 7 Arrivals - Wake Vortex Traffic Mix By Day
<table>
<thead>
<tr>
<th>Variable</th>
<th>Runway Occupancy time (H)</th>
<th>Runway Occupancy time (M)</th>
<th>Runway Occupancy time (S)</th>
<th>Runway Occupancy time (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample size</td>
<td>63</td>
<td>123</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>Average</td>
<td>65.5714</td>
<td>50.6504</td>
<td>49.1875</td>
<td>42.2</td>
</tr>
<tr>
<td>Median</td>
<td>68</td>
<td>50</td>
<td>50</td>
<td>42.5</td>
</tr>
<tr>
<td>Mode</td>
<td>54</td>
<td>50</td>
<td>57</td>
<td>29</td>
</tr>
<tr>
<td>Geometric mean</td>
<td>63.026</td>
<td>49.5155</td>
<td>48.5412</td>
<td>40.8778</td>
</tr>
<tr>
<td>Variance</td>
<td>267.829</td>
<td>118.278</td>
<td>65.0958</td>
<td>113.747</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>16.3655</td>
<td>10.8756</td>
<td>8.0682</td>
<td>10.6652</td>
</tr>
<tr>
<td>Standard error</td>
<td>2.06186</td>
<td>0.980619</td>
<td>2.01705</td>
<td>2.38482</td>
</tr>
<tr>
<td>Minimum</td>
<td>16</td>
<td>16</td>
<td>35</td>
<td>24</td>
</tr>
<tr>
<td>Maximum</td>
<td>97</td>
<td>103</td>
<td>62</td>
<td>61</td>
</tr>
</tbody>
</table>

Table 9 Arrivals Runway Occupancy Time per Aircraft Type (Runway 26L - 26 May 1989).
<table>
<thead>
<tr>
<th>Date</th>
<th>Heavy</th>
<th>Medium</th>
<th>Small</th>
<th>Light</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 July 1987</td>
<td>16.1</td>
<td>74.2</td>
<td>6.5</td>
<td>3.2</td>
</tr>
<tr>
<td>15 August 1987</td>
<td>17.2</td>
<td>74.1</td>
<td>8.6</td>
<td>0.0</td>
</tr>
<tr>
<td>22 August 1987</td>
<td>12.3</td>
<td>75.3</td>
<td>8.2</td>
<td>4.1</td>
</tr>
<tr>
<td>24 August 1987</td>
<td>11.4</td>
<td>77.3</td>
<td>6.8</td>
<td>4.5</td>
</tr>
<tr>
<td>Total Period</td>
<td>14.3</td>
<td>75.23</td>
<td>7.52</td>
<td>2.95</td>
</tr>
<tr>
<td>26 May 1989</td>
<td>22.4</td>
<td>54.6</td>
<td>8.6</td>
<td>14.5</td>
</tr>
<tr>
<td>23 June 1989</td>
<td>21.9</td>
<td>57.5</td>
<td>8.9</td>
<td>11.6</td>
</tr>
<tr>
<td>21 July 1989</td>
<td>21.5</td>
<td>56.9</td>
<td>10.4</td>
<td>11.1</td>
</tr>
<tr>
<td>8 September 1989</td>
<td>19.9</td>
<td>56.3</td>
<td>9.9</td>
<td>13.9</td>
</tr>
<tr>
<td>22 September 1989</td>
<td>19.2</td>
<td>58.9</td>
<td>9.9</td>
<td>11.9</td>
</tr>
<tr>
<td>Total Period</td>
<td>21.0</td>
<td>56.9</td>
<td>9.5</td>
<td>12.61</td>
</tr>
</tbody>
</table>

Table 10  Departures - Wake Vortex Traffic Mix By Day
<table>
<thead>
<tr>
<th>Variable</th>
<th>Take-off Roll (Heavy)</th>
<th>Take-off Roll (Medium)</th>
<th>Take-off Roll (Small)</th>
<th>Take-off Roll (Light)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample size</td>
<td>48</td>
<td>163</td>
<td>29</td>
<td>20</td>
</tr>
<tr>
<td>Average</td>
<td>52.2292</td>
<td>56.1534</td>
<td>45.3448</td>
<td>50.85</td>
</tr>
<tr>
<td>Median</td>
<td>46</td>
<td>52</td>
<td>42</td>
<td>52.5</td>
</tr>
<tr>
<td>Mode</td>
<td>44</td>
<td>41</td>
<td>41</td>
<td>62</td>
</tr>
<tr>
<td>Geometric mean</td>
<td>50.293</td>
<td>53.5033</td>
<td>43.041</td>
<td>47.8639</td>
</tr>
<tr>
<td>Variance</td>
<td>237.968</td>
<td>333.007</td>
<td>228.805</td>
<td>276.766</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>15.4262</td>
<td>18.2485</td>
<td>15.1263</td>
<td>16.6363</td>
</tr>
<tr>
<td>Standard error</td>
<td>2.22658</td>
<td>1.42933</td>
<td>2.80889</td>
<td>3.71999</td>
</tr>
<tr>
<td>Minimum</td>
<td>31</td>
<td>25</td>
<td>23</td>
<td>20</td>
</tr>
<tr>
<td>Maximum</td>
<td>96</td>
<td>134</td>
<td>78</td>
<td>79</td>
</tr>
<tr>
<td>Range</td>
<td>65</td>
<td>109</td>
<td>55</td>
<td>59</td>
</tr>
<tr>
<td>Lower quartile</td>
<td>42</td>
<td>43</td>
<td>35</td>
<td>38.5</td>
</tr>
<tr>
<td>Upper quartile</td>
<td>58.5</td>
<td>65</td>
<td>52</td>
<td>63.5</td>
</tr>
</tbody>
</table>

Table 11 Departure Take-off Roll / Aircraft Type (Runway 26L - 26 May 1989).

<table>
<thead>
<tr>
<th>Separations Categories</th>
<th>Route Followed</th>
<th>Nominal Separation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Same</td>
<td>Different</td>
</tr>
<tr>
<td>Normal Separations</td>
<td>106 (25)</td>
<td>76 (24)</td>
</tr>
<tr>
<td>Heavy leading non-Heavy</td>
<td>141 (2)</td>
<td>106 (4)</td>
</tr>
<tr>
<td>Medium leading non-Medium</td>
<td>56 (2)</td>
<td>120</td>
</tr>
<tr>
<td>Slow leading Fast</td>
<td>95 (2)</td>
<td>105 (4)</td>
</tr>
<tr>
<td>Fast leading Slow</td>
<td>41 (1)</td>
<td>120</td>
</tr>
</tbody>
</table>

(*) Mean (in seconds)  (**) Number of occurrences

Table 12 Departure Separations for runway 26L.
Departure Delays
Departures Measured Delay (Regulated and unregulated Traffic).

From CAA Gatwick Monitoring Tape/Summer 1989, one day operation was separated in order to show delays profile for departure regulated and unregulated traffic, Fig. 1 and 2. Holding point delay was observed for both types of traffic. (The observations were taken at 30 minute intervals, from 0600 to 1259)
Figure 2 Departure Measure Delay (unregulated Traffic)
APPENDIX 2

The Airport Scheduling

At Heathrow and Gatwick the unconstrained demand from airline operators has some years exceeded the declared runway capacities. This led to the creation of the Scheduling Committees at the two airports. A Scheduling Committee’s members comprise planning and scheduling representatives of the airlines using the airport.

The job of the Scheduling Committee is to co-ordinate the arrival and departure demand for all operators and to smooth it down to the runway and terminal capacity limits.

The focal points of the scheduling process calendar are the bi-annual IATA Scheduling Conferences in June and November for the forthcoming winter and summer seasons respectively for UK airports. A cornerstone of the process is the principle of "grandfather rights" which gives priority to established operations over new services.

At the IATA Conference the demand is adjusted through airline negotiations. Large adjustments - even several hours - in proposed timings sometimes need to take place so as to satisfy the capacity limitations on the runways, passenger terminals, parking positions and night restrictions. There are real cost attached to schedule adjustments away from optimum times - crew, ground handling, lost interline opportunities and other commercial objectives.

The Scheduling Committee Chairman can at any time ask for advice about proposed schedules regarding runway capacity aspects.

In recent years the "uncoordinated schedule", ie that prior to the IATA Conference, has been much above the declared runway capacities during the major part of the day on the busiest summer days for both Heathrow and Gatwick, ie would have implied very large delays. Unfortunately, the post-IATA Conference schedule is not the final version, because services can be consolidated, particularly charter operations, and this means that
the Gatwick Summer Schedule is not reasonably accurate until about March.

Final Scheduling Committee data is fed to BAA plc for display on the passenger terminal information boards. At this point the onus is on the carriers to ensure that extra services and also used by BAA to determine the extent to which any vacant slots can be allocated to general aviation. This is likely to occur frequently in 1988 summer peak hours.
APPENDIX 3

Wake vortex spacing requirements

1) Vortex Wake Categories

The Civil Aviation Authority (CAA), in its Aeronautical Information Service (AIS 1c 90/1986, defines the vortex wake categories of aircraft according to their maximum take-off weights as follows:

Four types of transport aircraft have an Maximum Take-off Weight of greater than 136 000 Kg., but have been re-classified to the medium weight category since experience has shown that they conform more to that group in terms of vortex propagation. These type are:

- Boeing 707 (all versions)
- McDonnell Douglas DC-8 (all versions)
- B.Ae. VC-10 and Super VC-10
- Ilyushin 62

Similarly, the Airbus A.310 which has a Maximum take-off Weight of 132 000 Kg. has been re-classified from the medium to the heavy category.
2) Wake Vortex Separation Minima

Contained in the CAA’s publication "Rules for Air Traffic Control" are the details of wake vortex separation minima, for two successive arrivals (A-A), two successive departures (D-D), a departure following an arrival (D-A) and an arrival following a departure (A-D).

<table>
<thead>
<tr>
<th>Leading Aircraft</th>
<th>Following Aircraft</th>
<th>Separation Minima Distance and Time Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ICAO</td>
</tr>
<tr>
<td></td>
<td></td>
<td>nm</td>
</tr>
<tr>
<td>Heavy</td>
<td>Heavy</td>
<td>4</td>
</tr>
<tr>
<td>Heavy</td>
<td>Medium</td>
<td>5</td>
</tr>
<tr>
<td>Heavy</td>
<td>Small</td>
<td>-</td>
</tr>
<tr>
<td>Heavy</td>
<td>Light</td>
<td>6</td>
</tr>
<tr>
<td>Medium</td>
<td>Heavy</td>
<td>3</td>
</tr>
<tr>
<td>Medium</td>
<td>Medium</td>
<td>3</td>
</tr>
<tr>
<td>Medium</td>
<td>Small</td>
<td>-</td>
</tr>
<tr>
<td>Medium</td>
<td>Light</td>
<td>4</td>
</tr>
<tr>
<td>Small</td>
<td>Heavy</td>
<td>-</td>
</tr>
<tr>
<td>Small</td>
<td>Medium</td>
<td>-</td>
</tr>
<tr>
<td>Small</td>
<td>Small</td>
<td>-</td>
</tr>
<tr>
<td>Small</td>
<td>Light</td>
<td>-</td>
</tr>
<tr>
<td>Light</td>
<td>Heavy</td>
<td>3</td>
</tr>
<tr>
<td>Light</td>
<td>Medium</td>
<td>3</td>
</tr>
<tr>
<td>Light</td>
<td>Small</td>
<td>-</td>
</tr>
<tr>
<td>Light</td>
<td>Light</td>
<td>3</td>
</tr>
</tbody>
</table>

These minima to be applied when an aircraft is operating directly behind another aircraft, and when crossing behind at the same altitude or less than 1000 ft. below.

* Separation for wake vortex reasons alone is not necessary.

Wake Vortex Spacing Minima for Arrivals
Wake Vortex Spacing Minima - Final Approach

<table>
<thead>
<tr>
<th>Leading Aircraft</th>
<th>Following Aircraft</th>
<th>Minimum Spacing at the Time Aircraft are Airborne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>Medium Departing</td>
<td>2 minutes</td>
</tr>
<tr>
<td></td>
<td>Small from the</td>
<td></td>
</tr>
<tr>
<td></td>
<td>or</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Light position</td>
<td></td>
</tr>
<tr>
<td>Medium or Small</td>
<td>Light</td>
<td>2 minutes</td>
</tr>
<tr>
<td>Heavy (Full length Takeoff)</td>
<td>Medium Departing</td>
<td>3 minutes</td>
</tr>
<tr>
<td></td>
<td>Small from an</td>
<td></td>
</tr>
<tr>
<td></td>
<td>or</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Light part of the</td>
<td></td>
</tr>
<tr>
<td></td>
<td>same runway</td>
<td></td>
</tr>
<tr>
<td>Medium or Small</td>
<td>Light</td>
<td>3 minutes</td>
</tr>
<tr>
<td>(Full length</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Takeoff)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Wake Vortex Spacing Minima for Departures

Wake Vortex Spacing Minima - Departures

Wake Vortex Spacing Minima - Displaced Landing Threshold

A separation of 2 minutes should be provided between a Medium, Small or Light aircraft when operating on a runway with a displaced runway threshold when:

- a) a departure follows a heavy arrival aircraft,
- b) an arrival follows a Heavy departure,

if the flight profiles are expected to cross.
3) Application of Wake Vortex Minima

When the separation minima normally required for IFR purposes is greater than for wake vortex, the IFR minima will apply.

Wake vortex minima may be applied for any situation not covered by specific time minima whenever a controller believes there is a potential hazard due to wake vortex.
A Greedy Heuristic for the One-Machine Scheduling Problem with due dates.

Here is considered a special one-machine scheduling problem*: n jobs $J_i (i = 1, \ldots, n)$ have to be processed on a machine. A release date $r_i$, a processing time $t_i$, a due date $d_i$ and a weight $w_i$ are connected with job $J_i$. Each solution can be described by a permutation of the job indices. If a permutation $p$ is chosen we denote by $S_i(p)$ the starting time of $J_i$ and by $C_i(p) = S_i(p) + t_i$ the completion time of $J_i$. Now is introduced a value $U_i$ with

$$ U_i = \begin{cases} 1 & \text{if } C_i(p) > d_i \\ 0 & \text{otherwise} \end{cases} $$

which indicates whether $J_i$ is late or not. A permutation which minimizes the objective $\sum_{i=1}^{n} W_i U_i$ is looked for. This problem is denoted as $n/1/r_i \geq 0/\sum w_i U_i$.

The mentioned problem is NP-hard, and has been tackled already through the one of Branch and Bound and Dynamic Programming techniques by many authors.

Here an insertion algorithm is given for the present scheduling problem. As regards the worst case behaviour, an example is present that shows this heuristic solution can be arbitrarily bad.

An insertion method which starts with a single job and complete step by step a subsequence by inserting a further job in the existing sequence is used. Here two questions are of interest:

(1) Which job will be inserted next into the subsequence?

(2) On which position will the chosen job be inserted?

In this algorithm the jobs are inserted according to non-increasing weights.

The position is determined in such a way that the maximum lateness $L_{max} = \max \{ L_i \} = \max \{ C_i - d_i \}$ of all inserted jobs is minimized. Then the insertion algorithm is follows:

**Step (1):** Determine $i \in H : = \{ 1, \ldots, n \}$ with maximal weight $w_i$ (if there exist several jobs select that $i$ with minimal $d_i$, if still more than one job exists choose $i$ with minimal $t_i$); $h : = 1 ; \; k : = \emptyset , \; H : = H \setminus \{ i \}$

If $r_i + t_i > d_i$ $\Rightarrow Z : = Z \cup \{ i \} , \; p : = \emptyset$ and go to Step(2);

$h : = h + 1 : \; K : = K \cup \{ i \} ; \; p : = ( i )$

**Step (2):** Determine $i \in H$ with maximal $w_i$ (if several $i$ exist perform as in Step (1)).

Determine the minimal position $g$ of an element in $p$ such that the completion time of the corresponding job is greater than $r_i$ ($g : = h$ if such an element does not exist).

Determine $L_{max}(p^j)$ for $j = g, \ldots, h$ where $p^j$ is obtained by inserting $i$ on position $j$ in $p$.

Determine $u \in \{ g, \ldots, h \}$ with minimal $L_{max}(p^u)$ (if $u$ is not uniquely determined choose the largest $u$).

If $L_{max}(p^u) > 0$ $\Rightarrow Z : = Z \cup \{ i \}$ and go to Step(3);
\[ h := h + 1; \quad k := k \cup \{ i \}; \quad p := p^u; \]

**Step (3):** \( H := H \setminus \{ i \}; \) if \( H \neq \emptyset \Rightarrow \) go to Step(2);

Let \( p^x \) be an arbitrary permutation of the elements of \( Z; p^I := (p, p^x) \) is the heuristic solution with \( F (p^I) = \sum \{ w_j \mid j \in Z \} \).

\( \mathcal{K} \) and \( Z \) represent the sets of indices of early and late jobs. We only mention that in the case \( g > 1 \) in Step(2) it is not necessary to consider the insertion of \( i \) on a smaller position than \( g \) since the objective value is not lower than for \( p^x \). The complexity of the above algorithm is \( O(n^2) \). The following example serves as illustration of algorithm I.

**Example 1:** Let

\[
\begin{array}{cccccccc}
  i & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\
  w_i & 10 & 8 & 7 & 5 & 3 & 2 & 1 \\
  r_i & 15 & 8 & 6 & 18 & 3 & 5 & 10 \\
  t_i & 4 & 8 & 7 & 8 & 6 & 5 & 7 \\
  d_i & 33 & 35 & 25 & 42 & 18 & 20 & 28
\end{array}
\]

The jobs are already numbered such that they are inserted in the above order. We obtain as heuristic solution \( p^I = (5, 6, 3, 2, 1, 4, 7) \) with \( Z = \{7\} \) and \( F (p^I) = 1 \). It is noted that \( p^I \) is also the optimum solution.

**Example 2:** Let

\[
\begin{array}{cccccccc}
  i & 1 & 2 & 3 & \ldots & n-1 & n \\
  w_i & 2 & 1 & 1 & \ldots & 1 & 1 \\
  r_i & 0 & 0 & 0 & \ldots & 0 & 0 \\
  t_i & n & 1 & 1 & \ldots & 1 & 1 \\
  d_i & n & 1 & 2 & \ldots & n-2 & n-1
\end{array}
\]

Obviously we have the optimum solution \( p^{opt} = (2, 3, \ldots, n-1, n, 1) \) with \( F (p^{opt}) = 2 \). Algorithm I yields \( p^I = (1, 2, \ldots, n-1, n) \)
with $F(p^I) = n-1$. Hence $F(p^I)/F(p^{opt}) = (n-1)/2$ unbounded increases with the number of jobs.
program tese;
uses Printer;
const
nsim = 1;
tempo = 4; slice = 1200; preco = 10;
naamin = 0; nadmin = 0;
trpmoy = 60; tdcmoy = 60;
tmind = 120; taxd = 240; trdmin = 30;
NS = 1; MS = 1;
var
  tatt, tintr, tlintr, tfintr, tfntr, poids, weight: array[1..100] of real;
  tdep, trdec, dtax, tcab, tdef, tfcs, tdee, retard, duree, at, dt,
  dducree, trpisatt: array[1..100] of real;
  time, tsm, mtba, tinit, tmax, tfini, tdum, tdumm, tdum1, tdum2, tt, td1, t0: real;
  zw, z, lw, l, i, l, j, l, je, jk, jmax, lord, lavion, ntr, ninf, nsup, ntottr, nntottr, h1, h2: integer;
  n, NN, nm, nq, nf, nfile, k, kk, kkk, num, nul, nur, naamax, nadmax, numwait: integer;
  s, cur, atraso: real;
  dur, cdur, w, wv, wfr, wtf, wtf, wtt: real;
  nor, ord, urd, quuu, avilb, navilb: array[1..100] of integer;
  h, mn, sec, tempol, tempo, ndur: integer;
procedure init;
begin
  tslm:= 1;
  tlnlt:= 18000;   (* 5 horas da manha *)
  tmax:= tslm*3600*tempo;
  tfnl:= tlnlt + tmax;
  (* mta:= int(tmax/naamin); *)
  tempol:= 5; tempof:= 5 + tempo;
  z:= 1; lr:= 1;
  naamax:= 60;
  nadmax:= 60;
  { nm:= round(tempo/slice) + 1; }
  dur:= 0.0;
end;
{***********************************************************************}
{***********************************************************************}
{***********************************************************************}
procedure chegadas;
begin
  randseed:= 111 + (z-1);
  { Geracao dos horarios de tocar na pista de aterrisagem *}
  { Geracao dos avloes por tipo *}
  l:= 1;
  while l.aamax do begin
    s:= random*10;
    if (s <= 0.5) then at[l]:= 1; { Heavy }
    if (0.5 < s) and (s 6.5) then at[l]:= 2; { Medium }
    if (6.5 < s) and (s 9.0) then at[l]:= 3; { Small }
    if (9.0 < s) and (s 10.0) then at[l]:= 4; { Light }
    l:= l+ 1;
  end;
  s:= 0.0;
  l:= 1;
  tatt[l]:= int(tlnlt + tmax*random);
  l:= 2;
while I <= aamax do
  begin
    t0 := tmax*random;
    if (t0 < 120.0) then t0 := 120.0;
    t dum := Int(tinit + t0);
    tatt[i] := t dum;
    j := 1;
    while j < I do
      begin
        if (t dum < tatt[j]) then
          begin
            l := l;
            while j > l do
              begin
                jk := j-1;
                tatt[jk] := tatt[jk];
                j := jk;
              end;
            tatt[i] := t dum;
            t dum := 1000000.0;
          end;
        l := l + 1;
      end;
    I := I + 1;
  end;
{ I := 1;
  while I <= aamax do
    begin
      h := round(Int(tatt[i]/3600));
      mn := round(Int((tatt[i]-3600.0*h)/60));
      sec := round(tatt[i]-3600.0*h-60*mn);
      writeln(Lst,'a/c: ',I, ' hour: ',h, ' min: ',mn,
        ' sec: ',sec, ' landing time: ',tatt[i]);
      I := I + 1;
    end;
}

{* Ordonacao dos avloes na aterrisagem *}
I := 1;
while i <= aamax do
    begin
        j:= 1;
        s:= 0.0;
        while j <= 6 do
            begin
                s:= s + random;
                j:= j + 1;
            end;
        trpisatt[i]:= trpmoy + round((s/6-0.5)*10);
    end;
    if i > 1 then
        begin
            j:= 1;
            while (j < i) do
                begin
                    if (tatt[i] < (tatt[i] + trpmoy))
                        then tatt[i]:= tatt[i] + trpmoy;
                    j:= j + 1;
                end;
            i:= i + 1;
        end;
    { writeln(Lst,' Arrival touch down time '); }
    i:= 1;
    while i <= naamax do
        begin
            h:= round(int(tatt[i]/3600));
            mn:= round(int((tatt[i]-3600.0*h)/60));
            sec:= round(tatt[i]-3600*h-60*mn);
            { writeln(Lst,' a/c: ',i,' hour: ',h,' mn: ',mn,' sc: ',
                sec,' Landing time: ',round(int(tatt[i])),
                ' Gap = ',round(int(tatt[i]-tatt[i-1])),
                ' tkr: ',round(trpisatt[i])); }
            i:= i + 1;
        end;
Entrada da tabela dos instantes de chegada das aeronaves

procedure tabxeg;
begin
end;

procedure gaps;
begin
  ntr := 1;
  tintr[ntr] := tinit;
  tfntr[ntr] := tfini;
  i := 1;
  while i <= aamax do
    begin
      if (tatt[i] - tintr[ntr]) >= tmind then
        begin
          tfntr[ntr] := tatt[i];
          ntr := ntr + 1;
          tintr[ntr] := tatt[i] + trplsatt[i];  { trpmoy; }
          tfntr[ntr] := tfini;
        end
      else
        begin
          tintr[ntr] := tatt[i] + trplsatt[i];  { trpmoy; }
          tfntr[ntr] := tfini;
        end;
      i := i + 1;
    end;
  if (tfini - tintr[ntr]) >= tmind

- Page 211 -
then \( \text{tfntr}[\text{ntr}] := \text{tfinl} \)
else \( \text{ntr} := \text{ntr} - 1; \)
\( \text{ntottr} := \text{ntr}; \)
if \( \text{tfntr}[\text{ntottr}] = (\text{tinit} + \text{tmax}) \) then \( \text{tfntr}[\text{ntottr}] := \text{tinit} + \text{tmax} + 2*\text{slice} \)
else
begin
\( \text{ntottr} := \text{ntottr} + 1; \)
\( \text{tlntr}[\text{ntottr}] := \text{tinit} + \text{tmax}; \)
\( \text{tfntr}[\text{ntottr}] := \text{tfntr}[\text{ntottr}] + 2*\text{slice}; \)
end;
If \( I_r = 1 \) then
begin
\{ \\
writeln(Lst,' Arrivals Gaps'); \\
\}
\( l := 1; \)
while \( (l <= \text{ntottr}) \) do
begin
\( \text{duree}[l] := \text{tfntr}[l] - \text{tlntr}[l]; \)
\{ \\
writeln(Lst,' a/c : ',l,' start : ',round(\text{tlntr}[l]),' end : ',round(\text{tfntr}[l]),''Gap : ',round(\text{duree}[l])); \\
\}
\( l := l + 1; \)
end;
end;
\( I_r := I_r + 1; \)
end;
\{******************************************************************\}
\{ Departure Aircraft Generation \}
\{******************************************************************\}
procedure partida;
begin
\( l := 1; \)
\( \text{tdep}[l] := \text{int}((\text{tinit} + \text{tmax} \times \text{random})/60) \times 60; \)
\( l := 2; \)
while \( l <= \text{nadmax} \) do
begin
\( \text{tdum} := \text{int}((\text{tinit} + \text{tmax} \times \text{random})/60) \times 60; \)
\}
tdep[l] := tdum;
  j := 1;
  while j < l do
    begin
      if(tdum < tdep[j]) then
        begin
          j := l;
          while j > j do
            begin
              k := j-1;
              tdep[j] := tdep[k];
              j := k;
            end;
          tdep[l] := tdum;
          tdum := 1000000.0;
        end;
      end;
      j := j + 1;
    end;
  l := l + 1;
end;
end; while l <= admax do
begin
  j := 1;
  s := 0.0;
  while j <= 6 do
    begin
      s := s + random;
      j := j + 1;
    end;
  trdec[l] := tdcmoy + round((s/6-0.5)*20);
  trdec[l] := tdcmoy;
  if l > 1 then
    begin
      while (j < l) do
        begin
          ...
        end
    end;
if(tdep[i] < tdep[j]) then tdep[i] := tdep[j];
    j := j + 1;
end;
end;

i := i + 1;
end;
end;

{ +----------------------------------------------------- + }
{ | } Entrada da tabela de partidas | }
{ +----------------------------------------------------- + }
{ procedure tabpart; begin
end; }
{----------------------------------------------------------}

{*****************************************************************************}
procedure gerassal;
begin
    i := 1;
    { writeln(Lst,'Departure weight table '); }
    while i <= nadmax do
    begin
        { writeln(Lst, 'a/c: ',i,' Time dep: ',round(int(tdep[i])),
             ' weight: ',round(int(polds[i]))); }
        i := i + 1;
        end;
    { }
h := round(int(tdep[i]/3600));
mn := round(int((tdep[i]-h*3600.0)/60));
writeln(Lst,'a/c depart: ',i,' h: ',h,' mn: ',mn);

end;

procedure fcfs;
begin

{** Taxi time generation roll out **}
{i:=1;
while i<=nadmax do
begin
s := random*10;
k := 0;
while k<10 do
begin
dtax[i] := taxi;
if ((s >= k) and (s <= (k+1))) then
dtax[i] := taxi + k*30;
k := k + 1;
end;

tcab[i] := tdep[i] + dtax[i];
nor[i] := 1;
retard[i] := 999999999.9;
avlbl[i] := 0;
i := i + 1;
end;

{* Take-off roll generation *}

{i:=1;
while i <= nadmax do
begin
s := random*4;

}
k:= 0;
while k <= 4 do begin
    trdec[i] := tdcmoy;
    if ((s > k) and (s < (k + 1))) then
        trdec[i] := trdmin + k*20;
    k:= k + 1;
end;
l:= l + 1;
end;

{* Classificação por ordem de chegada na cabeceira da pista *}
l:= 1;
while l <= nadmax do begin
    j:= 1;
    while j <= admax do begin
        if (tcab[i] = tcab[j]) then nor[i] := nor[i] + 1;
        if (tcab[i] = tcab[j]) and (j) then nor[i] := nor[i] + 1;
        j:= j + 1;
    end;
l:= l + 1;
end;

{* calcul dos atrasos *}
ntr:= 1;
while ntr <= ntottr do begin
    ttintr[ntr]:= tintr[ntr];
    tffntr[ntr]:= tffntr[ntr];
    duree[ntr]:= duree[ntr];
    ntr:= ntr + 1;
end;
nntottr:= ntottr;
j:= 1;
while j <= nadmax do
begin
  if (nor[j] = j) then
    begin
      l := j;
      j := nadmax + 1;
    end
  else j := j + 1;
end;
tdum1 := tcab[l];
tdum2 := tcab[l] + trdec[l];
ntr := 1;
while ((ntr <= nntottr) and (navlib[l] = 0)) do
  begin
    if (ttfnnr[ntr] > = tdum1) and (dduree[ntr] > = trdec[l])) then
      begin
        if (tdum1 <= ttfnnr[ntr]) then
          begin
            tdum1 := ttfnnr[ntr];
            navlib[l] := 1;
            ttfnnr[ntr] := tdum1 + trdec[l];
          end
        if (tdum1 > ttfnnr[ntr]) and (tdum2 <= ttfnnr[ntr])) then
          begin
            navlib[l] := 1;
            tdm1 := ttfnnr[ntr];
            ttfnnr[ntr] := tdum1;
            js := nntottr + 1;
            while (js > = (ntr + 2)) do
              begin
                j := js - 1;
                ttfnnr[js] := ttfnnr[ntr];
                ttfnnr[js] := ttfnnr[ntr];
                dduree[js] := dduree[ntr];
                js := js - 1;
              end;
            nntottr := nntottr + 1;
          end
      end
  end;
}
nn := ntr + 1;
ttlntr[nn] := tdum2;
ttfmtr[nn] := tdum1;
end;
ntr := ntr + 1;
end;
tfcfs[i] := tdum1;
retard[i] := tdum1 - tcab[i];
j := j + 1;
end;
end;

{*******************************************************************************
{ Queue initialisation and criterion points
*******************************************************************************
procedure winit;
begin
  l := 1;
  while l <= nadmax do
    begin
      quuu[i] := 9999; nor[i] := 9999; ord[i] := 9999;
      avlib[i] := 0; tdef[i] := tdep[i]; tdee[i] := tdep[i];
      s := random*10;
      if (s <= 0.5) then poids[i] := 10;
      if (0.5 < s) and (s <= 6.5) then poids[i] := 7;
      if (6.5 < s) and (s <= 9.0) then poids[i] := 3;
      if (9.0 < s) and (s <= 10.0) then poids[i] := 1;
      
        if (s <= 10.0) then poids[i] := 10;
        if (2.5 < s) and (s <= 5.0) then poids[i] := 7;
        if (5.0 < s) and (s <= 7.5) then poids[i] := 3;
        if (5.0 < s) and (s <= 10.0) then poids[i] := 1;
      
        l := l + 1;
    end;
end;
procedure queue;
begin
    nq:= 0;
    i:= 1;
    while i <= nadmax do
        begin
            if (navlib[i] = 0) and (tdep[i] <= (time + 10*sllce)) then
                begin
                    nq:= nq + 1;
                    quuu[nq]:= i;
                end;
            i:= i + 1;
        end;
end;

procedure peso;
begin
    i:= 1;
    while i <= nadmax do
        begin
            if (navlib[i] = 0) then
                weight[i]:= poids[i] * (tt-tdep[i]) * (tt-tdep[i])
            else weight[i]:= -999999999999999999999999.0;
            i:= i + 1;
        end;
end;

procedure ordena;
begin
    k:= 1;
    while k <= nq do
        begin
        end;
```plaintext
nor[k] := 1;
j := 1;
while j <= q do
begin
  if (weight[quuu[k]] < weight[quuu[j]]) then
    nor[k] := nor[k] + 1;
  if (weight[quuu[k]] = weight[quuu[j]]) then
    if (k > j) then nor[k] := nor[k] + 1;
  j := j + 1;
end;
k := k + 1;
end;
k := 1;
while k <= q do
begin
  j := 1;
  while j <= nq do
begin
    if (nor[j] = k) then
      begin
        urd[k] := quuu[j];
        ord[k] := urd[k];
      end;
    j := j + 1;
  end;
k := k + 1;
end;
end;

{********************************************************************}
{********************************************************************}
procedure reslot;
begin
  ntr := 1;
  while ntr <= ntottr do
begin
    tlntr[ntr] := tlntr[ntr];
    tfntr[ntr] := tfntr[ntr];
    duree[ntr] := duree[ntr];
```

- Page 220 -
ntr := ntr + 1;
end;
nntottr := nntottr;
end;

procedure rereslot;
begin
ntr := 1;
while ntr <= nntottr do
begin
  tintr[ntr] := ttintr[ntr];
tfntr[ntr] := ttfntr[ntr];
duree[ntr] := dduree[ntr];
ntr := ntr + 1;
end;
nntottr := nntottr;
end;

procedure prepare;
begin
  jk := 1;
  while jk <= nadmax do
  begin
    navllb[jk] := avllb[jk];
tdee[jk] := tdee[jk];
jk := jk + 1;
  end;
end;

procedure insert;
begin
  ntr := 1;
  while ((ntr <= nntottr) and (navllb[n] = 0)) do
  begin
    if (ttfntr[n] >= tdfm1) and (dduree[n] = tdc moy) then
      begin
        if (tdum1 <= ttintr[n]) then
          begin
            \[\text{...}\]
          end;
    end;
end;
end;

tdum:= tlintr[ntr]-taxl;
navlib[i]:= 1;
tlintr[ntr]:= tdum + taxl + tdc moy;
end;
if((tdum1 > tlintr[ntr]) and (tdum2 < = tfntr[ntr])) then
begin
    navlib[i]:= 1;
    tdumm:= tfntr[ntr];
tfntr[ntr]:= tdum1;
    j:= nntottr + 1;
    while (j > = (ntr+2)) do
        begin
            j:= j-1;
            tlintr[j]:= tlintr[j];
tfntr[j]:= tfntr[j];
tduree[j]:= tduree[j];
j:= j-1;
        end;
    nntottr:= nntottr + 1;
tlintr[ntr+1]:= tdum2;
tfntr[ntr+1]:= tdumm;
end;
end;
ntr:= ntr + 1;

procedure select;
begin
    ww:= 0.0;
k:= 1;
i:= urd[1]; tdum:= tdee[i]; tdum1:= tdum + taxl; tdum2:= tdum1 + tdc moy;
insert;
td1:= tdum; ww:= ww + polds[i]*(tdum-tdep[i])*(tdum-tdep[i]); k:= k + 1;
while k <= nq do
    begin
        l:= urd[k];
        tdum:= tdee[l];
tdum1 := tdum + tax1;
{Insert}
ww := ww + polds[i]*(tdum - tdep[i])*(tdum - tdep[i]);
k := k + 1;
end;

procedure horopt;
begin
{Insert}

procedure scrabble;
begin

- Page 223 -
if \( n = 1 \) then 
    begin 
    end; 
if \( n = 2 \) then 
    begin 
    end; 
end; 
  if \( nq > 3 \) then 
    begin 
    case \( n \) of 
        1: begin 
        end; 
        2: begin 
        end; 
        3: begin 
        end; 
        4: begin 
        end; 
        5: begin 
        end; 
        6: begin 
        end; 
    end; 
{k := 1; 
while \( k \leq q \) do 
    begin 
    j := urd[k]; 
    tdee[j] := tdee[j]; 
    k := k + 1; 
    end;
end;

k:=2;
while k <= q do
begin
    j:= urd[k];
    kk:= 1;

    while kk < k do
    begin
        j:= urd[kk];
        if (tdeel[j] < (tdeel[j] + tdcmoy)) then tdeel[j] := tdeel[j] + tdcmoy;
        kk:= kk+1;
    end;
    k:= k+1;
end;
end;

{*******************************************************************************}
procedure monitor;
begin
    nf:= 1;
    while (tt < (time+slice)) and (nf < = nfile) do
begin
    queue; peso; ordena; ww:= 0.0;
    if nq= 1 then NN:= 1; if nq= 2 then NN:= 2;
    if nq > = 3 then NN:= 3;
    n:= 1;
    select;reslot;
    li:= urd[1];
    tdef[li]:= td1;
    w:= ww; prepare;
    n:= 1;
    while n < = NN do
    begin
        scrabble;
        select;reslot;prepare;
        if ww < w then
        begin
            li:= urd[1];
        end;
    end;
end;
tdef[i]:= td1;
    w:= ww;
end;
    n:= n + 1;
end;
l:= 1;

tdum:= tdef[i]; tdum1:= tdum + tax; tdum2:= tdum1 + tdc moy;
navlib[i]:= 0; Insert;
    rer eslot;
tdef[i]:= tdum;
avlib[i]:= 1;
    prepare;
tt:= tdef[i] + tdc moy;
    reslot; prepare;
    queue; peso; ordena;
nf:= nf + 1;
end;
end;

{*****************************************************}
procedure salida;
begin
{    writeln(Lst,'  Delay Table');
}
l:= 1; wft:= 0.0; wtt:= 0.0; wff:= 0.0; wtf:= 0.0;
while l <= nadmax do
    begin
{        writeln(Lst,' a/c: ',l,' FCFS: ',round(int(retard[i])),
        'SAIDA: ',round(int(tdef[i]-tdep[i])));
    }
    wft:= wft + poids[i]*retard[i]/nadmax;
    wff:= wff + preco*poids[i]*retard[i]/nadmax;
    wtt:= wtt + poids[i]*(tdef[i]-tdep[i])/nadmax;
    l:= l + 1;
end;
writeln(Lst,' Delays ponderados: rule FCFS: ',round(int(wft)));
writeln(Lst,' rule SAIDA: ',round(int(wtt)));

- Page 226 -
while iw <= 100 do
begin
  time:= tinit + (iw-1)*slice;
  tt:= time; reslot; prepare;
  queue; nfile := nq;
  if nfile >= 1 then monitor;
  iw:= iw+1;
end;

gerassal;
horopt;
saida;
end.

{Entrada da tabela chegada ou chegadas aleatórias:"chegadas"}
{Entrada da tabela partidas ou partidas aleatórias: "partidas"}
{tabxeg; gaps; tabpart;

chegas; gaps; partidas;
fcs;
{tabxeg; gaps; tabpart;

iw := 1;
winlt;
while iw <= 100 do
begin
  time:= tinit + (iw-1)*slice;
  tt:= time; reslot; prepare;
  queue; nfile := nq;
  if nfile >= 1 then monitor;
  iw:= iw+1;
end;

gerassal;
horopt;
saida;
end.

begin
  writeln(Lst, ' Total (arrivals) = ',naamax,
          ' Total (departures) = ',nadmax,
          ' Time window = ',slice);
  writeln(Lst, ' Start time = ',round(tinit),
          ' End time = ',round(tfinl));

MAIN PROGRAM

begin
  init;

  writeln(Lst, ' Total (arrivals) = ',naamax,
          ' Total (departures) = ',nadmax,
          ' Time window = ',slice);
  writeln(Lst, ' Start time = ',round(tinit),
          ' End time = ',round(tfinl));

  {Entrada da tabela chegada ou chegadas aleatórias:"chegadas"}
  {Entrada da tabela partidas ou partidas aleatórias: "partidas"}
  {tabxeg; gaps; tabpart;

  chegadas; gaps; partidas;
fcs;
  {tabxeg; gaps; tabpart;

  iw := 1;
  winlt;
  while iw <= 100 do
  begin
    time:= tinit + (iw-1)*slice;
    tt:= time; reslot; prepare;
    queue; nfile := nq;
    if nfile >= 1 then monitor;
    iw:= iw+1;
  end;

  gerassal;
  horopt;
saida;
end.

end;
writeln(Lst, '

Extra fuel : rule FCFS: ',round(int(wff));
rule SAIDA: ',round(int(wtf));
end;

{***************************** MAIN PROGRAM ****************************}
{***************************** MAIN PROGRAM ****************************}
{***************************** MAIN PROGRAM ****************************}

begin
  init;

  writeln(Lst, ' Total (arrivals) = ',naamax,
          ' Total (departures) = ',nadmax,
          ' Time window = ',slice);
  writeln(Lst, ' Start time = ',round(tinit),
          ' End time = ',round(tfinl));

  {Entrada da tabela chegada ou chegadas aleatórias:"chegadas"}
  {Entrada da tabela partidas ou partidas aleatórias: "partidas"}
  {tabxeg; gaps; tabpart;

  chegadas; gaps; partidas;
fcs;
  {tabxeg; gaps; tabpart;

  iw := 1;
  winlt;
  while iw <= 100 do
  begin
    time:= tinit + (iw-1)*slice;
    tt:= time; reslot; prepare;
    queue; nfile := nq;
    if nfile >= 1 then monitor;
    iw:= iw+1;
  end;

  gerassal;
  horopt;
saida;
end.

end.