Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.
SEARCH AND RESCUE MANAGEMENT: MODELLING AND DEVELOPMENT OF HEURISTIC STRATEGIES WITHIN A SIMULATION ENVIRONMENT

A THESIS PRESENTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN OPERATIONS RESEARCH AT MASSEY UNIVERSITY, PALMERSTON NORTH, NEW ZEALAND.

Fiona Helen Wharton
2000
Where such references to "man", "he", or "his" appear in the body of this thesis, they have been used only to avoid the awkwardness of "man/woman", "she/he", or "his/her" constructions, and as such should be understood in their generic context.
Abstract

The search for a lost person on land has been the subject of relatively little research to date in comparison to other search problems. This thesis addresses this imbalance by examining the search for a stationary object that does not attempt to avoid detection. The problem is defined as a synthesis of the coverage, routing, and allocation problems that exist in the literature, and its complexity and unique aspects are discussed.

A physical model of the search terrain is developed using a Triangulated Irregular Network (TIN). This model incorporates the vegetation and natural features of the terrain, and is extended to model access paths and traversal speeds between any two points. A visibility model is developed over the TIN in order to define a detection model for both a human subject and any clues placed by him. Correction factors are used to model visibility and traversal speeds under different search environments.

Methods to define search regions as components of the elements of the TIN are described. Heuristic resource allocation methods are then developed for both the reconnaissance and general phases of a search operation. These methods allocate search tasks to resources individually or in parallel, and in real-time. Dynamic heuristic search strategies to respond to changing search conditions and the discovery of new information are then developed.

A Discrete Event Simulation (DES) model of a Search and Rescue (SAR) operation is developed. This model incorporates: siting a search base; search resource deployment and searching; clue and subject detection; communication between resources and search management; flooding and resource deployment under adverse weather conditions; and responsiveness of the subject over time.

The simulation model is used to perform some preliminary computational experiments on a restricted set of resource allocation methods and search strategies. Initial trends indicated from these experiments are: the general superiority of methods which do not
restrict the set of regions to be allocated for searching to an initial primary search area; the dominance of a night searching strategy; the dominance of using a sound detection method when a subject is responsive; and the benefits of applying diversifying search strategies.
Acknowledgements

The completion of this thesis has been achieved with the input, resources and encouragement of many people.

- **Tony** - my husband and best friend, for his unending encouragement, love and understanding, and for his patient data entry and editing.

- **My family** - for their years of support and continued attempts to understand what this “OR thing” is all about, and for their practical help with proofreading, editing and diagram creation.

- **John Giffin** - my chief supervisor, for his perseverance and technical critique.

- **Mark Johnston** - for his patience, time and practical expertise in sourcing, trialling and installing software for me, and showing me what to do with it. Particular thanks are due for creating the majority of the diagrams.

- **Fana To’omaga** - my brilliant typist who deciphered my scrawlings and dictation to put many of these words on paper; and to **Workbridge** for providing her funding.

- **Ross Gordon, Emergency Management Ltd.** - for his realist’s point of view, total enthusiasm for the research, and the contacts he enabled with overseas SAR experts.

- **New Zealand Police Search and Rescue personnel** - particularly Inspector John Meads, NZ SAR Coordinator, for allowing me access to Police resources and providing the opportunity to participate in the national SAR training course.

- **Richard Rayner** - for initially showing me the ropes with C, \LaTeX{} and UNIX.
• My good friends - for keeping me sane. Special thanks to Kathryn Redhead, Shalome Campbell, Sharlene Pilkinton, Bernadette Murray and Nic Gidden, for their help with typing and proofreading in the final weeks.
The following specific terms are referenced throughout this thesis:

**Binary Search**  A search method used to eliminate areas that the subject has not passed through.

**Coverage (C)**  The ratio of search effort to the size of the search area.

**Critical Separation**  The spacing of ground search resources at a distance equal to two times the visibility measure of that terrain.

**Double Strip Search**  A form of grid searching where a region is searched twice from two different angles.

**Hot Spots**  Likely places for physical clues to be detected.

**Lateral Range (x)**  The perpendicular distance between a search resource and the search object at the point on the resource’s path which is closest to the object.

**Lateral Range Curve**  A curve depicting the cumulative probability of detection for a given search resource as a function of x, with one pass.

**Mattson Consensus Technique**  A technique which guides search management to a consensus decision in defining POA values for search regions.

**PDEN**  The Probability of Density. A measure used to rank search regions calculated on the POA value divided by the size of the search region.

**Perimeter Cut**  A search technique where resources search along the boundaries of the search area for clues.
PLS  The Point Last Seen represents the last known location of a search object.

POA  The Probability Of Area.\(^1\) The probability that the search object is located within a given search region.

POD  The Probability Of Detection. The conditional probability that if the search object is in the search region it will be detected by the search resource. We use the word detection in the context of detection with recognition.

POD\text{cum}  The cumulative probability of detection over a number of successive searches of a search region.

POS  The Probability Of Success of a search as measured by the detection of the search object and calculated as POA \(\times\) POD.

POS\text{cum}  The cumulative probability of success over the search operation.

Priority Search Area \((G_P)\)  The subset of the search region graph which is identified as having the highest likelihood of containing the subject and on which searching is concentrated. This area is of a size that is able to be searched by the search effort on hand within one search period.

Probability Map  A map of the search area depicting POA values in each subarea.

PSR  The Probable Success Rate. A measure of the rate of POS increase to be expected when searching a region.

Repeated Expansion  A search technique which begins by searching a small area centred on a specific reference point, and then successively re-searching this area in incremental expansions in an outwards direction.

Risk Map  A visual map identifying hazards over a given region.

ROC  Relevance Of a Clue to the search operation.

ROW  The Rest Of the World. A pseudo-region representing any area outside of the defined search area.

Search Priority  A myopic planning tool which ranks search regions for searching based on their contribution to POS and the time taken to achieve this.

Search Effort \((Z)\)  The area which can be effectively swept by a given search resource given its sweep width and the distance travelled by the resource.

\(^1\)Also referred to in the literature as the Probability of Containment.
Search Object  The object of a search. This includes human subjects as well as organic and inorganic clues.

Search Path  The path of edges and/or triangular regions that a search resource is assigned.

Search Region  A well-defined region assigned to a search resource for searching.

Search Region Graph \((G)\)  The 2-D graph derived from the TIN.

Search Resource  A resource assigned to the search area to search for the search object. Such resources include human searchers, aircraft, dogs, and mechanical or electronic devices. Also referred to as a sensor, we refer particularly to a human searcher when using the term search resource within the body of the thesis.

Sector Stripping  A method which removes search resources from one search region in favour of searching an alternative region in order to increase POS.

Sector Laddering  A method which ranks search regions in a ladder formation with the top-most region having highest priority and regions being placed at the bottom of the ladder upon search completion. Regions whose priority is adjusted throughout the operation are moved to appropriate positions on the ladder.

Sound Sweep  A search technique where search resources moving in a grid formation aim to detect a responsive subject by calling out at regular time intervals and listening for a response.

Sweep Width \((W)\)  The area under the lateral range curve - "a measure of the amount of 'detecting' being done" [150, page 4-4]. The sweep width differs for different search objects, search resources, and search conditions.

TIN  Triangulated Irregular Network. A digital terrain model which geometrically partitions the terrain into triangles by a triangulation generated over a representative set of data points.

Track Traps  Ground cleared for the purpose of observing if fresh tracks are laid.

Trail-Based POA  A method of assigning POA values to a search area based on the possible behaviour of a subject initially known to have followed a marked path. POA values are estimated from the findings of a team who follow this path identifying and ranking decision points where the subject may have left the path.
The following variable definitions are utilized in the algorithm descriptions:

- $start_k$ = the starting position (vertex) of resource $k$
- $resources$ = number of search resources
- $path_{k,j}$ = vertex at position $j$ on the nodepath of resource $k$
- $num_k$ = number of vertices in the path of resource $k$
- $time_k$ = amount of time required to complete the path of resource $k$
- $path\_limit$ = the duration limit of any search path assignment
- $path_{1,j}$ = vertex at position $j$ in the intended path of the subject
- $num_{I}$ = number of vertices in the intended path of the subject
- $time_{I}$ = amount of time needed to complete the intended path of the subject
- $c_{i,j}$ = time cost of traversing edge $(i,j)$
- $stpath_{i,j}$ = shortest path from vertex $i$ to vertex $j$
- $D_{i,j}$ = time length of shortest path from vertex $i$ to vertex $j$
- $PLS$ = point which the subject was last seen at
- $POS_{i,j}$ = POS value predicted from the search of edge $(i,j)$
- $base$ = search base
- $limit_k$ = 1 if resource $k$ is at their search hour limit, = 0 otherwise
- $POA_i$ = POA of region $i$
- $POD_i$ = POD level at which region $i$ is to be searched at
- $POD_{cum,i}$ = cumulative POD of region $i$
- $area_i$ = area of region $i$
- $nregions$ = number of regions in the search region graph
- $find\_team$ = resource which detects the subject
- $urgency$ = urgency level of the search
- $period\_start$ = commencement time of the next search period
\textit{period\_end} = time at which the current search period will be completed

\textit{down\_time} = amount of non-searching time between consecutive search periods

\textit{weather\_level} = level of current weather conditions

\textit{new\_weather} = predicted weather level arising at \textit{weather\_clock}

\textit{flood\_time} = the time at which regions of the TIN susceptible to flooding will flood and become impassable

\textit{lost\_region} = the region of the TIN in which the subject is located

\textit{cost\_change} = array which monitors the fraction of the current search task completed under differing environmental conditions, for each active resource

\textit{periodct} = index of search periods

\textit{recall} = indicator of whether or not resources are being recalled to the search base

\textit{suspend} = indicator of whether or not the operation is being suspended
# Table of Contents

Acknowledgements .......................... vii
Glossary of Terms ........................... ix
Table of Contents ........................... xv
List of Figures ............................... xix
List of Tables ................................ xxiii
List of Algorithms ........................... xxix

1 Introduction ............................... 1
  1.1 Introduction ................................ 1
  1.2 Thesis Objectives and Approach .......... 2

2 Search Concepts ........................... 7
  2.1 Search Theory ............................... 7
  2.2 Application to Land SAR ................... 9
  2.3 Subject Movement and Location .......... 10
  2.4 Search Object Detection ................... 27
  2.5 Success of a Search Operation .......... 34
  2.6 Location Probability Distribution Update 35
  2.7 Search Measurements ...................... 36

3 Current Search Methods ................... 39
  3.1 New Zealand SAR Organization .......... 40
  3.2 Urgency ................................. 41
  3.3 Definition of the Search Area .......... 42
  3.4 Search Base Location ..................... 43
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>Search Resources</td>
<td>44</td>
</tr>
<tr>
<td>3.6</td>
<td>Communication</td>
<td>48</td>
</tr>
<tr>
<td>3.7</td>
<td>Resource Allocation</td>
<td>50</td>
</tr>
<tr>
<td>3.8</td>
<td>Clue Detection</td>
<td>60</td>
</tr>
<tr>
<td>3.9</td>
<td>Search Methods and Tactics</td>
<td>61</td>
</tr>
<tr>
<td>3.10</td>
<td>Rescue</td>
<td>71</td>
</tr>
<tr>
<td>3.11</td>
<td>Search Suspension</td>
<td>71</td>
</tr>
<tr>
<td>3.12</td>
<td>The Global Positioning System</td>
<td>72</td>
</tr>
<tr>
<td>3.13</td>
<td>Computerized Search Planning</td>
<td>74</td>
</tr>
<tr>
<td>3.14</td>
<td>Limitations of Current Land SAR Approaches</td>
<td>79</td>
</tr>
<tr>
<td>4</td>
<td>Modelling The Search Terrain</td>
<td>81</td>
</tr>
<tr>
<td>4.1</td>
<td>Geographical Information Systems</td>
<td>81</td>
</tr>
<tr>
<td>4.2</td>
<td>Digital Terrain Models</td>
<td>83</td>
</tr>
<tr>
<td>4.3</td>
<td>The Topography</td>
<td>98</td>
</tr>
<tr>
<td>4.4</td>
<td>Cost Structure</td>
<td>99</td>
</tr>
<tr>
<td>4.5</td>
<td>Visibility and Sound Measures</td>
<td>101</td>
</tr>
<tr>
<td>4.6</td>
<td>Weather and Light Conditions</td>
<td>104</td>
</tr>
<tr>
<td>4.7</td>
<td>Search Regions</td>
<td>106</td>
</tr>
<tr>
<td>5</td>
<td>Detection And Clue Modelling</td>
<td>109</td>
</tr>
<tr>
<td>5.1</td>
<td>Detection Models</td>
<td>109</td>
</tr>
<tr>
<td>5.2</td>
<td>Modelling the Path of the Subject</td>
<td>129</td>
</tr>
<tr>
<td>5.3</td>
<td>Clue Modelling</td>
<td>132</td>
</tr>
<tr>
<td>6</td>
<td>Placing The SAR Problem In Context</td>
<td>145</td>
</tr>
<tr>
<td>6.1</td>
<td>Dynamism</td>
<td>145</td>
</tr>
<tr>
<td>6.2</td>
<td>Coverage</td>
<td>146</td>
</tr>
<tr>
<td>6.3</td>
<td>Vertex Routing</td>
<td>155</td>
</tr>
<tr>
<td>6.4</td>
<td>Arc Routing</td>
<td>158</td>
</tr>
<tr>
<td>6.5</td>
<td>Arc and Vertex Routing</td>
<td>164</td>
</tr>
<tr>
<td>6.6</td>
<td>Partitioning</td>
<td>165</td>
</tr>
<tr>
<td>6.7</td>
<td>Scheduling</td>
<td>166</td>
</tr>
<tr>
<td>6.8</td>
<td>The SAR Problem</td>
<td>167</td>
</tr>
<tr>
<td>6.9</td>
<td>Problem Formulation</td>
<td>170</td>
</tr>
<tr>
<td>6.10</td>
<td>Unique Aspects of the Problem</td>
<td>185</td>
</tr>
<tr>
<td>7</td>
<td>The Reconnaissance Search: Edge Routing</td>
<td>187</td>
</tr>
<tr>
<td>7.1</td>
<td>Preamble</td>
<td>187</td>
</tr>
<tr>
<td>7.2</td>
<td>Modelling Current Search Practices</td>
<td>188</td>
</tr>
<tr>
<td>7.3</td>
<td>Additional Search Heuristics</td>
<td>204</td>
</tr>
<tr>
<td>7.4</td>
<td>Adapting Approaches In the Literature</td>
<td>213</td>
</tr>
<tr>
<td>7.5</td>
<td>A Special Case</td>
<td>218</td>
</tr>
</tbody>
</table>
### 7.6 Improvement Strategies

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>221</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>7.7 Bilevel Routing</th>
</tr>
</thead>
<tbody>
<tr>
<td>222</td>
</tr>
</tbody>
</table>

### 8 General Search Phase

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1</td>
<td>Prior Edge Searching</td>
</tr>
<tr>
<td>8.2</td>
<td>Methods of Individual Region Coverage</td>
</tr>
<tr>
<td>8.3</td>
<td>Modelling Traversal of a Triangular Region</td>
</tr>
<tr>
<td>8.4</td>
<td>Search Region Definition</td>
</tr>
<tr>
<td>8.5</td>
<td>Search Region Definition Heuristic</td>
</tr>
<tr>
<td>8.6</td>
<td>Resource Allocation</td>
</tr>
<tr>
<td>8.7</td>
<td>Heuristics</td>
</tr>
<tr>
<td>8.8</td>
<td>Path Generation</td>
</tr>
</tbody>
</table>

### 9 Dynamic Search Strategies

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.1</td>
<td>Real-Time Decision Problems</td>
</tr>
<tr>
<td>9.2</td>
<td>Solution Approaches</td>
</tr>
<tr>
<td>9.3</td>
<td>Real-Time Decision Systems</td>
</tr>
<tr>
<td>9.4</td>
<td>Relevance of Solution Approaches in the Literature</td>
</tr>
<tr>
<td>9.5</td>
<td>Dynamic Strategies</td>
</tr>
</tbody>
</table>

### 10 Search And Rescue Simulation

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1</td>
<td>Introduction</td>
</tr>
<tr>
<td>10.2</td>
<td>Problem Description</td>
</tr>
<tr>
<td>10.3</td>
<td>The Simulation Model</td>
</tr>
<tr>
<td>10.4</td>
<td>Assumptions of the Model</td>
</tr>
<tr>
<td>10.5</td>
<td>Inputs To The SAR Simulation</td>
</tr>
<tr>
<td>10.6</td>
<td>Simulation Objectives</td>
</tr>
<tr>
<td>10.7</td>
<td>Implementation</td>
</tr>
</tbody>
</table>

### 11 Simulation Modules

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.1</td>
<td>Initialization</td>
</tr>
<tr>
<td>11.2</td>
<td>Search Base Allocation</td>
</tr>
<tr>
<td>11.3</td>
<td>Search Urgency</td>
</tr>
<tr>
<td>11.4</td>
<td>Search Periods</td>
</tr>
<tr>
<td>11.5</td>
<td>Event Functions</td>
</tr>
<tr>
<td>11.6</td>
<td>Utility Functions</td>
</tr>
<tr>
<td>11.7</td>
<td>Communication</td>
</tr>
<tr>
<td>11.8</td>
<td>Resourcing</td>
</tr>
<tr>
<td>11.9</td>
<td>Resource Redeployment</td>
</tr>
<tr>
<td>11.10</td>
<td>Subject Detection</td>
</tr>
<tr>
<td>11.11</td>
<td>Subject Rescue</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>225</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>279</th>
</tr>
</thead>
<tbody>
<tr>
<td>299</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>317</th>
</tr>
</thead>
<tbody>
<tr>
<td>317</td>
</tr>
<tr>
<td>319</td>
</tr>
<tr>
<td>321</td>
</tr>
<tr>
<td>324</td>
</tr>
<tr>
<td>327</td>
</tr>
<tr>
<td>333</td>
</tr>
<tr>
<td>335</td>
</tr>
<tr>
<td>336</td>
</tr>
<tr>
<td>343</td>
</tr>
<tr>
<td>345</td>
</tr>
</tbody>
</table>
12 Simulation Experimentation

12.1 Introduction ............................................. 351
12.2 TIN Generation ........................................... 351
12.3 SAR Problem Instance ..................................... 357
12.4 Computational Experiments ................................ 363
12.5 Problem Instance A ....................................... 367
12.6 Problem Instance B ....................................... 391
12.7 Problem Instance C ....................................... 409
12.8 Clue Analysis ............................................ 424
12.9 Analysis of Resource Allocation Methods .................. 431
12.10 Comparison of Problem Instances ....................... 439
12.11 Conclusion ............................................... 440

13 Conclusions And Avenues For Further Research ............ 443

13.1 The Physical Terrain Model ................................. 443
13.2 Visibility, Detection and Clue Modelling .................... 445
13.3 Resource Allocation Methods and Search Strategies .......... 446
13.4 Simulation Model ........................................ 449
13.5 Conclusion ............................................. 451

Bibliography ................................................ 453
List of Figures

3.1 Double strip search. ................................................. 66
3.2 Sector search by an aircraft. ..................................... 66
3.3 Repeated expansion search after three searches. .......... 67

4.1 Triangulated Irregular Network (viewed from above). ........ 85
4.2 Empty circle criterion. ........................................... 92
4.3 Constrained Delaunay triangulation. ............................. 94
4.4 Lawson's local optimization procedure. ......................... 95

5.1 Lateral range curve of the definite range detection model. ... 110
5.2 Lateral range curve of the $M - Beta$ detection model. .... 111
5.3 Lateral range curve of the inverse cube model of detection under ideal search conditions. ................................. 112
5.4 POD vs. coverage comparison of classical detection models. 114
5.5 Lateral range curve for the critical separation detection model. 115
5.6 Two searchers spaced at critical separation. ................. 116
5.7 POD vs. coverage comparison of the critical separation detection model. 116
5.8 Non-symmetric lateral range curve. .............................. 124
5.9 Distance representation of the visual detection of a subject. 128
5.10 Exit vertex determination for a triangular region. ........... 131
5.11 Path generated in line with historical POA values. .......... 131
5.12 Physical clue placement. ........................................ 132
5.13 Subject and clue lateral range curves. ........................ 136
5.14 Clue position for a resource entering an edge region at vertex $b$. 138
5.15 Clue position for a resource entering a triangular region at vertex $c$ and exiting at vertex $a$. .............................. 139
5.16 POA update upon clue detection. ............................... 141
5.17 Updating location probabilities for an altered subject route. 143
7.1 Edges adjacent to the intended path of the subject. 198
7.2 Search path of alternating moves. 199
7.3 A perimeter search by two search resources when subject intentions or PLS are known. 202
7.4 A perimeter search by four search resources, from an interior search base, when no intended path or PLS information is known. 203
7.5 Division of a WPP tour into \( k \) components. 216
7.6 Partitioning the primary search area via the regions incident to an interior base vertex. 217
7.7 \( k \) search paths over \( k \) matched edges. 219
7.8 An original matching compressed to pseudo-vertices and then expanded to give three search paths. 220
7.9 A search path from the search base through a pseudo-vertex. 220
7.10 A search path beginning from a vertex of degree two. 220

8.1 Paint brush analogy of the visibility cover arising from edge searching. 226
8.2 A triangle reduced in depth along the two searched edges. 227
8.3 “Y-shape”. 228
8.4 “Curved” triangle. 228
8.5 “Arrow shaped region”. 228
8.6 Triangle with a “bite” removed. 229
8.7 Pattern of searcher spacing when conducting a sweep of a triangular region. 231
8.8 Width Strip Search. 232
8.9 Recursive Perimeter Search. 233
8.10 Pivoting between successive perimeters. 234
8.11 Medial axis of a triangular region. 236
8.12 Simple triangulation of a triangular search region. 236
8.13 Delaunay triangulation of the initial medial axis triangulation. 237
8.14 Petal traversal to cover a triangular region. 237
8.15 Bisection Triangulation — first, second and third bisection. 238
8.16 Hill search as one component. 239
8.17 Traversal approximation of a triangular region. 240
8.18 ‘Close to equiangular triangles’ partition of a region. 245
8.19 Amalgamation of adjacent triangular regions into a single search region. 246
8.20 Trail based POA segmentation method. 248
8.21 Segmentation of a triangular region. 249
8.22 Local optimization procedure to select the orientation of a region search when the region is added to the end of an existing path. 254
8.23 Binary tree through a TIN. 254
8.24 Creation of a primary search area. 267
8.25 The cheapest insertion of a region into a search path. 270
9.1 A general architecture for the SAR problem ........................................ 287

10.1 A broad schema of the SAR simulation model. ................................. 312
10.2 Path representation. ................................................................. 313
10.3 State changes over search task execution. ................................. 314
10.4 Incomplete assignments. ......................................................... 315

11.1 Visual representation of consecutive search periods. ....................... 324
11.2 Search interruptions. .............................................................. 335
11.3 Redeployment from within a triangular region. ............................ 341

12.1 The range of z-coordinates (in m) for each grid square of the TIN construction grid. ......................................................... 353
12.2 Allocating a triangle spanning several grid squares, to a single grid square. ......................................................... 353
12.3 The TIN used in experimental computation. .................................. 357
12.4 The edge classifications of the TIN used in experimental computation. ......................................................... 358
12.5 Simulated weather conditions under weather scenario one. ................ 361
12.6 Simulated weather conditions under weather scenario two. ............... 361
12.7 The growth of POS\textsubscript{cum} under the benchmark method from the exterior base with night searching strategy. ................................................. 386
12.8 The growth of POS\textsubscript{cum} under the single task method from the exterior base. ......................................................... 386
12.9 The growth of POS\textsubscript{cum} under the path scan method from the exterior base. ......................................................... 387
12.10 The growth of POS\textsubscript{cum} under the primary search area method from the exterior base. ......................................................... 387
12.11 Comparison of the growth of POS\textsubscript{cum} over resource allocation methods from the exterior base for problem instance A. ................................................. 388
12.12 Adjacency of the \textit{lost}\textsubscript{region} to regions in which clues are detected. ......................................................... 427
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>The cause of NZ land SAR operations.</td>
<td>18</td>
</tr>
<tr>
<td>2.2</td>
<td>The activities resulting in NZ land SAR operations.</td>
<td>19</td>
</tr>
<tr>
<td>2.3</td>
<td>The subjects of NZ land SAR operations.</td>
<td>19</td>
</tr>
<tr>
<td>2.4</td>
<td>The highest rating categories of injuries received by subjects of NZ land SAR operations.</td>
<td>20</td>
</tr>
<tr>
<td>2.5</td>
<td>The status of equipment carried by subjects of NZ land SAR operations.</td>
<td>20</td>
</tr>
<tr>
<td>2.6</td>
<td>The intention record left by subjects of NZ land SAR operations.</td>
<td>20</td>
</tr>
<tr>
<td>2.7</td>
<td>The weather conditions of NZ land SAR operations.</td>
<td>24</td>
</tr>
<tr>
<td>2.8</td>
<td>The total operation hours of NZ land SAR operations.</td>
<td>24</td>
</tr>
<tr>
<td>2.9</td>
<td>Generalities for USA land SAR operations.</td>
<td>24</td>
</tr>
<tr>
<td>2.10</td>
<td>Probability decision data for determining trail-based POA values.</td>
<td>25</td>
</tr>
<tr>
<td>2.11</td>
<td>Wartes’ field trial POD data for ground searchers in moderately dense underbrush.</td>
<td>31</td>
</tr>
<tr>
<td>2.12</td>
<td>USA AFRCC POD data for air searches of lost people.</td>
<td>32</td>
</tr>
<tr>
<td>3.1</td>
<td>The utilization of volunteers in NZ land SAR operations.</td>
<td>41</td>
</tr>
<tr>
<td>3.2</td>
<td>Matching of sweep search technique to subject type.</td>
<td>70</td>
</tr>
<tr>
<td>4.1</td>
<td>Visibility and sound measures.</td>
<td>104</td>
</tr>
<tr>
<td>5.1</td>
<td>Coverage and effort values for different searcher spacings for the critical separation detection model.</td>
<td>117</td>
</tr>
<tr>
<td>5.2</td>
<td>Wartes’ field data in critical separations.</td>
<td>119</td>
</tr>
<tr>
<td>5.3</td>
<td>High visibility sweep data for dense coniferous forest in winter.</td>
<td>120</td>
</tr>
<tr>
<td>5.4</td>
<td>Standard visibility sweep data for dense coniferous forest in winter.</td>
<td>120</td>
</tr>
<tr>
<td>5.5</td>
<td>Low visibility sweep data for dense coniferous forest in winter.</td>
<td>124</td>
</tr>
<tr>
<td>5.6</td>
<td>Body sweep data for dense coniferous forest in winter.</td>
<td>125</td>
</tr>
<tr>
<td>5.7</td>
<td>Quiet voice response sound sweep data for dense coniferous forest in winter.</td>
<td>125</td>
</tr>
<tr>
<td>5.8</td>
<td>Environmental degradation factors of clue detectability.</td>
<td>137</td>
</tr>
</tbody>
</table>
8.1 An example problem for the PSR allocation heuristic .......... 260
11.1 Urgency response level ........................................ 322
11.2 Time durations of communication events ...................... 334
11.3 Redeployment path duration limits ............................. 338
11.4 Path cost factors for gradient changes between edge traversals .... 349
12.1 The percentage limit of the number of grid squares classified by each terrain type. 354
12.2 The number of regions classified by terrain type ................ 356
12.3 Resource allocation methods for problem instance A from the interior base located at vertex 0 .......... 368
12.4 Resource allocation methods for problem instance A from the exterior base located at vertex 27 .............. 369
12.5 Path scan method of resource allocation for all resource criteria, for problem instance A from the interior base located at vertex 0 .................. 372
12.6 Path scan method of resource allocation for all resource criteria, for problem instance A from the exterior base located at vertex 27 .................. 373
12.7 Ranking of secondary selection criteria for the hybrid path scan method for problem instance A .................. 374
12.8 Hybrid path scan methods of resource allocation for problem instance A from the interior base located at vertex 0 .................. 376
12.9 Hybrid path scan methods of resource allocation for problem instance A from the exterior base located at vertex 27 .............. 377
12.10 Sound sweep search method for a responsive subject in the first two periods, for problem instance A from the exterior base located at vertex 27 .............. 378
12.11 Sound vs. visual searching strategies from the exterior search base .............. 379
12.12 Sound sweep search method for an unresponsive subject for those methods detecting a responsive subject via sound within the first two periods, for problem instance A from the exterior base located at vertex 27 .............. 380
12.13 Sound sweep search method for a responsive subject in the first four periods using the search priority region criterion, for problem instance A from the exterior base located at vertex 27 .............. 382
12.14 Sound sweep search method for an unresponsive subject in the first four periods using the search priority region criterion, for problem instance A from the exterior base located at vertex 27 .............. 382
12.15 Permitting re-searching of a region within the same search period, for problem instance A from the exterior base located at vertex 27 .............. 384
12.16 Not permitting re-searching of a region within the same search period for the single task allocation method, for problem instance A from the exterior base located at vertex 27 .............. 385
12.17 Performance ratios for visual search resource allocation methods for problem instance A when deploying from the exterior base .............. 389
12.18 Performance ratios for visual search resource allocation methods for problem instance A when deploying from the interior base. ........................................ 390
12.19 Performance ratios comparing sound and visual searching resource allocation methods for problem instance A when deploying from the exterior base. ... 390
12.20 Resource allocation methods for problem instance B from the exterior base located at vertex 27. ................................................................. 393
12.21 Resource allocation methods for problem instance B from the interior base located at vertex 13. ................................................................. 394
12.22 Ranking of secondary selection criteria for the hybrid path scan method for problem instance B. ................................................................. 396
12.23 Hybrid resource allocation methods for problem instance B from the exterior base located at vertex 27. ................................................................. 397
12.24 Hybrid resource allocation methods for problem instance B from the interior base located at vertex 13. ................................................................. 398
12.25 Primary search area restrictions for the path scan allocation method, for problem instance B from the exterior base located at vertex 27. ................. 400
12.26 Re-searching options for the path scan allocation method, for problem instance B from the exterior base located at vertex 27. ........................................ 400
12.27 Resource criteria for the path scan allocation method, for problem instance B from the exterior base located at vertex 27. ........................................ 401
12.28 Comparison of selected resource allocation methods for problem instance B from the interior base located at vertex 13, under visual and sound sweep searching for both weather scenarios. ........................................ 403
12.29 Resource allocation methods for problem instance B from the exterior base located at vertex 27, when no intended route knowledge is known. .......... 406
12.30 Resource allocation methods for problem instance B from the interior base located at vertex 0, when no intended route knowledge is known. .......... 407
12.31 Resource allocation methods for problem instance B from the interior base fixed at vertex 13, when no intended route knowledge is known. .......... 408
12.32 Performance ratios for visual search resource allocation methods for problem instance B when deploying from the exterior base. ...................... 409
12.33 Performance ratios for visual search resource allocation methods for problem instance B when deploying from the interior base. ...................... 409
12.34 Comparison of resource allocation methods for problem instance C under weather scenario one, from the exterior base located at vertex 27. .......... 412
12.35 Comparison of resource allocation methods for problem instance C under weather scenario two, from the exterior base located at vertex 27. .......... 413
12.36 Comparison of resource allocation methods for problem instance C under weather scenario one, from the interior base located at vertex 0. .......... 414
12.37 Comparison of resource allocation methods for problem instance C under weather scenario two, from the interior base located at vertex 0. .......... 415
12.38 Ranking of region criteria under the primary search area method for problem instance C .................................................. 416
12.39 Comparison of hybrid resource allocation methods for problem instance C under weather scenario one, from the exterior base located at vertex 27 .................................................. 417
12.40 Comparison of hybrid resource allocation methods for problem instance C under weather scenario two, from the exterior base located at vertex 27 .................................................. 418
12.41 Rankings of secondary selection criteria for the hybrid path scan method from the exterior base located at vertex 27 .................................................. 419
12.42 Comparison of subject detection times between weather scenarios when deployment is from the exterior base located at vertex 27 .................................................. 421
12.43 Comparison of subject detection times between weather scenarios when deployment is from the interior base located at vertex 0 .................................................. 421
12.44 Performance ratios for visual search resource allocation methods for problem instance C, when deploying from the exterior base under weather scenario one .................................................. 423
12.45 Performance ratios for visual search resource allocation methods for problem instance C, when deploying from the interior base under weather scenario one .................................................. 423
12.46 Performance ratios for visual search resource allocation methods for problem instance C, when deploying from the exterior base under weather scenario two .................................................. 423
12.47 Performance ratios for visual search resource allocation methods for problem instance C, when deploying from the interior base under weather scenario two .................................................. 423
12.48 Clue placement and detectability for problem instance A .................................................. 424
12.49 Clue placement and detectability for problem instance B .................................................. 425
12.50 Clue placement and detectability for problem instance C .................................................. 425
12.51 Clue detection under the benchmark method from the exterior base, under night searching and least hours resource criterion .................................................. 426
12.52 Benchmark allocation method with least hours resource criterion, for problem instance B from the exterior base located at vertex 27, under night searching when no clues are detected in region 137 .................................................. 428
12.53 Benchmark allocation method with least hours resource criterion, for problem instance B from the exterior base located at vertex 27, under night searching when clue detection in region 137 is assured .................................................. 428
12.54 Clue detection and subsequent POA update for problem instance C when clues were detected outside of the lost region by the primary search area method .................................................. 432
12.55 Ranking of resource criteria for the benchmark method by problem instance .................................................. 432
12.56 Ranking of region criteria for the single task method by problem instance .................................................. 433
12.57 Best solution ratios for each region selection criterion for the single task method by problem instance .................................................. 433
12.58 Ranking of region criteria for the primary search area method by problem instance .................................................. 434
12.59 Best solution ratios for each region selection criterion for the primary search area method by problem instance .................................................. 435
12.60 Ranking of region criteria for the path scan method by problem instance .................................................. 435
12.61 Best solution ratios for each region selection criterion for the path scan method
by problem instance. ................................................. 436
12.62 Ranking of secondary region criteria for the hybrid path scan method by initial
criterion and problem instance. ................................. 437
12.63 Best solution ratios of secondary region criteria for the hybrid path scan method
by initial criterion and problem instance. ........................ 438
12.64 Average CPU time (in seconds) for each resource allocation method by problem
instance. ................................................................. 439
List of Algorithms

5.1 function responsiveness_level() ........................................ 129
7.1 function follow_path(PLS) ........................................ 191
7.2 function incident_PLS(PLS, tnum) .................................. 192
7.3 function towards_PLS(PLS, tnum) .................................. 194
7.4 function hazard_route(resource) .................................... 195
7.5 function hazard_parallel(tnum) .................................... 196
7.6 function intersecting_path(tnum) .................................. 200
7.7 function perimeter(tnum) ........................................... 201
7.8 function hedging_search_path(k, obj) .............................. 206
7.9 function minisum_time(candidate, ct, t, start) ..................... 207
7.10 function minimax_time(candidate, ct, t, start) .................... 208
7.11 function minisum_static(candidate, ct, start) ...................... 209
7.12 function minimax_static(candidate, ct, start) ...................... 210
7.13 function base_arc_allocation() .................................... 212
7.14 function nearest_neighbour(partition) ............................. 213
8.1 function PSR_heuristic(k) ........................................... 261
8.2 function primary_search_area() ..................................... 268
8.3 function generate_path(resource, cost) ............................ 271
8.4 function generate_kpaths(resources, ct, cost) ....................... 272
8.5 function alternative_path(resource, limit, cost) .................... 273
9.1 function POA_response() ........................................... 293
9.2 function reactive_modify() ......................................... 296
9.3 function incremental_modify() ....................................... 297
9.4 function deliberative_modify() ...................................... 297
11.1 function begin_search_operation() .................................. 320

xxix
11.2 function base_allocation() ........................................ 320
11.3 function urgency() .................................................. 323
11.4 function urgency_upgrade() ....................................... 324
11.5 function begin_search_period() ................................. 325
11.6 function end_search_period() .................................... 328
11.7 function next_period() ............................................. 329
11.8 function redirect(a, b, resource) ................................. 340
11.9 function return_to_base(resource) ............................... 342
11.10 function flood_check(resource) ................................. 344
11.11 function subject_located() ...................................... 345
11.12 function rescuers_required() .................................... 347
11.13 function subject_carry_out() ................................... 348
12.1 function vegetation_allocation() ............................... 354