DYNAMIC ROUTING WITH COMPETITION: FOUNDATIONS AND STRATEGIES

A thesis presented in partial fulfilment
of the requirements for
the degree of Doctor of Philosophy in
Operations Research at
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Mark Richard Johnston

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Errata and Addenda

P 7 line 2	Replace "evaluate these difficulty" by "evaluate the difficulty".
P 17 line 11	Replace '[35]' by '[35, page 475]'.
P 19 line −12	Replace "Brideau and Cavalier" by "Brideau and Cavalier [28, page 1]".
P 21 line −17	Replace "They adopt" by "Desrochers, Lenstra and Savelsbergh [54, page 323] adopt".
P 21 line −1	Replace "which will be useful to" by "that will be useful in".
P 23 line 18	Replace '[60]' by '[60, page 12]'.
P 26 line 13	Replace 'interesting' by 'interestingly'.
P 26 line 14	Replace '[146]' by '[146, page 1105]'.
P 28 line 10	Replace '[7]' by '[7, page 206]'.
P 31 line 14	Replace "Is it possible communicate between decision makers?" by "Is communication possible between decision makers?".
P 34 line −16	Delete 'of these'.
P 39 line −6	Replace "move continuously at the same constant speed in the Euclidean plane" by "move continuously at unit speed in the Euclidean plane and may instantaneously change direction".
P 40 line 3	Replace '[7]' by '[7, pages 11–18]'.
P 43 line −7	Replace "principles make" by "principles that make".
P 46 line 3	Insert after the first sentence: "Let $d_{\mathcal{X}i}$ be the distance from player $\mathcal{X}$'s current location to the location of prize i (at unit speed this is equivalent to the minimum possible time for player $\mathcal{X}$ to reach prize i)."
P 46 line 23	Replace "players prize i" by "players share prize i".
P 47 line −17	Delete 'a'.
P 47 line −15	Delete 'it'.
P 47 line −11	Replace "median prize of move" by "median prize or move".
P 49 line −18	Replace "at least on prize" by "at least one prize".
P 52 line 4	Replace "subpath, but not necessarily committing to entire, but" by "subpath, not necessarily committing to an entire subpath, but".
P 53 line −13	The definition given for *Farthest Insertion* is that of *Most Expensive Insertion*. For **Farthest Insertion**, select vertex k not on the subpath such that d_{ik} (for $k \in$ subpath) is maximized. Insert vertex k between subpath edge (i, j) such that $d_{ik} + d_{kj}$ is minimized.
P 54 line −1	Replace "guaranteed to player $\mathcal{A}$" by "guaranteed to player $\mathcal{A}$ if targeted first".
P 55 line −1	Replace "higher likelihood" by "higher likelihood of capture".
P 58 line 8	Delete 'we'.
P 59 line −14	Insert new paragraph "Let $\wp$ denote a problem instance defined by the number of prizes, the location of each prize, the value of each prize, the initial location of each player, the overall deadline, and the step size. The guaranteed value of a maximal guaranteed subpath for player $\mathcal{A}$ is denoted $\Gamma_{\mathcal{A}}(\wp)$ and the guaranteed value of a maximal guaranteed subpath for player $\mathcal{B}$ is denoted $\Gamma_{\mathcal{B}}(\wp)$."
P 61 line −1	Replace 'paranoid' by 'GUARANTEE-SUBPATH'.
P 63 line −10	Replace "We can calculate the **cooperative value**, Ω, which is" by "For a problem instance $\wp$, we can calculate the **cooperative value**, $\Omega(\wp)$, which is".
P 63 line −5, −1	Replace 'Ω' by '$\Omega(\wp)$'.
P 64 line 8	Replace "select between them." by "select between them?"
P 68 line −15	Replace "is the defined" by "is then defined"
P 68 line −13	Replace 'apply' by 'applying'.
P 93 line 6	Delete comma.
P 93 line 13	Replace "$d_{\mathcal{A}1} < d_{\mathcal{B}1}$ and $d_{\mathcal{A}2} = d_{\mathcal{B}2}$" by "$d_{\mathcal{A}i_1} < d_{\mathcal{B}i_1}$ and $d_{\mathcal{A}i_2} = d_{\mathcal{B}i_2}$".
P 93 line 19	Replace "$\mathcal{A}$—∘ i_1 and $\mathcal{B}$—∘ i_1 is a Nash equilibrium in which the players share the sequence $i_1 \twoheadrightarrow i_2$" by "$\mathcal{A}$—∘ i_2 and $\mathcal{B}$—∘ i_2 is a Nash equilibrium in which the players share the sequence $i_2 \twoheadrightarrow i_1$".

P 93 line 22	Replace "$\mathcal{A} \multimap \mathrm{argmax}\{v_1, v_2\}$ and $\mathcal{B} \multimap i_2$, for a reward of $\max\{\frac{1}{2}(v_1 + v_2), v_1\}$ to player $\mathcal{A}$ and $\min\{\frac{1}{2}(v_1 + v_2), v_2\}$ to player $\mathcal{B}$" by "$\mathcal{A} \multimap \mathrm{argmax}\{v_{i_1}, v_{i_2}\}$ and $\mathcal{B} \multimap i_2$, for a reward of $\max\{\frac{1}{2}(v_{i_1} + v_{i_2}), v_{i_1}\}$ to player $\mathcal{A}$ and $\min\{\frac{1}{2}(v_{i_1} + v_{i_2}), v_{i_2}\}$ to player $\mathcal{B}$".
P 94 line −12	Replace 'max' by 'min'.
P 94 line −11	Replace 'of' by 'or'.
P 94 line −10	Replace 'max' by 'min'.
P 103 line 18	Replace '$\mathcal{B}$' by '$\mathcal{A}$'.
P 109 line −13	Replace '$\mathcal{B}$safety-window' by '$\mathcal{B}$-safety-window'.
P 117 line −12	Replace last '+' by '$\geq$'.
P 118	Replace '$\Omega(\mathcal{A}, \mathcal{B})$' by '$\Omega(\wp)$', replace '$\Gamma(\mathcal{A})$' by '$\Gamma_A(\wp)$', and replace '$\Gamma(\mathcal{B})$' by '$\Gamma_B(\wp)$'.
P 118 line 15	Replace "every prize of sequence of prizes" by "every prize or sequence of prizes".
P 118 line 17	Replace 'paranoid' by 'guaranteed'.
P 118 line −1	Delete the redundant condition "and $d_{Ai_2} + d_{i_1 i_2} < d_{Bi_1}$".
P 119 line 1	Replace "$\mathcal{A} \rhd (i_2 \to i_1)$ is accessible but $\mathcal{A} \rhd (i_1 \to i_2)$ is not accessible" by "$\mathcal{A} \rhd (i_1 \to i_2)$ is accessible but $\mathcal{A} \rhd (i_2 \to i_1)$ is not accessible".
P 119 line 6	Replace '$\Omega(\mathcal{A}, \mathcal{B})$' by '$\Omega(\wp)$'.
P 133 line −4	Replace '$\Gamma(\mathcal{A}\|\mathcal{B})$' by '$\Gamma_A(\wp)$' and replace $\Omega(\mathcal{A}, \mathcal{B})$' by '$\Omega(\wp)$'.
P 136	Replace '$\Gamma(\mathcal{A}\|\mathcal{B})$' by '$\Gamma_A(\wp)$', replace $\Gamma(\mathcal{B}\|\mathcal{A})$' by '$\Gamma_B(\wp)$', and replace $\Omega(\mathcal{A}, \mathcal{B})$' by '$\Omega(\wp)$'.
P 139 line −1	Replace $\Omega(\mathcal{A}, \mathcal{B})$' by '$\Omega(\wp)$'.
P 146 line 2	Replace 'engine' by 'engines'.
P 170 line −13	Replace 'define' by 'determine'.
P 187 line −12	Replace 'prosed' by 'proposed'.
P 192 line −8	Delete 'the'.
P 196 line 15	Replace '$\Gamma_A(\mathcal{A} \rhd x\mathcal{B} \rhd y)$' by '$\Gamma_A(\mathcal{A} \rhd x, \mathcal{B} \rhd y)$'.
P 198 line 3	Replace "which make" by "that would make".
P 202	In the first table replace '$v_{i_1} < i_2 v_{i_3}$' by '$v_{i_1} < 2v_{i_3}$' and in the second table replace '$v_{i_2} < i_2 v_{i_3}$' by '$v_{i_2} < 2v_{i_3}$'.
P 206 line −20, −18	Replace '$\Gamma(\mathrm{j}, \mathcal{X})$' by '$\Gamma_X(\mathrm{j})$'.
P 206 line −19	Replace '$\Gamma(\mathrm{j})$' by '$\Omega(\mathrm{j})$'.
P 210 line 19	Replace 'that' by 'there'.
P 210 line −15	Replace 'provide' by 'provides'.
P 213 line 10	Replace 'defined' by "defined by".
P 213 line −17	Replace 'local-optima' by "local optimum".
P 217 line 4	Replace "swap to clusters" by "swap two clusters".
P 220 line 22	Delete "in an $\mathcal{X}$-future-family".
P 225 line −10	Before "Table 7.2(d) illustrates" insert the sentence "This exhibits a potential drawback of enforcing the *cluster-no-return* rule."
P 233 line −13	Replace '[29]' by '[29, page 111]'.
P 241 line −10	Replace 'lemma' by 'theorem'.
P 245 line 10	Replace '$\mathcal{A} \to 14 \to 12 \to 12$' by '$\mathcal{A} \to 14 \to 12 \to 13$'.
P 245 line 11	Replace '$\mathcal{A} \to 11 \to 9 \to 6 \to 7 \to 8$' by '$\mathcal{B} \to 11 \to 9 \to 6 \to 7 \to 8$'.
P 245 line −11	Replace 'playerA$\to 14 \to 12 \to 13$' by '$\mathcal{A} \to 14 \to 12 \to 13$'.
P 245 line −11	Replace '199' by '179'.
P 247	The caption for Table 7.4(d) should read "Player $\mathcal{B}$ FAMILY-PRIZE-GUARANTEE Subpath".
P 251 line −15	Replace 'posible' by 'possible'.
P 254 line 30	Add to the end of the paragraph: "In each case the two player game table indicates the *structure* of the root game table and '□' indicates an entry remaining to be evaluated."
P 261 line −6	Replace "clusters [2] and 35]" by "clusters [2] and [3]".
P 281 line 6	Replace "which is even more confusing" by "which is interesting since both players were previously trying to avoid a tactical conflict".
P 281 line −10	Add to the end of the paragraph: "Cycling occurs when players perpetually retargeting in response to the opponent retargeting. It would eventually be resolved as the players move closer to their respective candidate target clusters but may be detected and resolved earlier by switching to a MAXIMIN evaluator."
P 283 line 10	Replace 'governed' by "governed by".
P 284 line −11	Replace "be following in" by 'follow'.
P 286 line 1	Replace "to straightforward" "to be straightforward".
P 287 line 16	Move □ to the right hand side.
P 302 line −15	Delete "in a player $\mathcal{X}$ future-family".
P 305 line −20	Delete "in a player $\mathcal{A}$ future-family".
P 305 line −11	Replace '$\mathcal{G}_h + 1$' by '$\mathcal{G}_{h+1}$'.

P 337 line −7	Replace 'between' by 'from'.
P 340 line −9	Insert: "In the latter two grid-structures, players are located near to the centre of a grid-cell to minimize the edge effects in the initial planning paths."
P 366 line 7	Replace "measure a strategies" by "measure a strategy's".
P 387 line −10	Replace "but a similarly" by "but are similarly".
P 389	Delete prize 1 from Table 9.7(b) and Table 9.7(d).
P 392 line −10	Replace "is one which is hard to predict" by "is one for which it is hard to predict".
P 393	Delete prize 1 from Table 9.9(b) and Table 9.9(d).
P 400	In Table 10.1 replace '//PRIZE-PARANOID' by '//PRIZE-GUARANTEE'.
P 404 line −14	Replace "A ORIGINAL-DT" by "An ORIGINAL-DT".
P 407	The second part of Figure 10.1 should have label '(b)'.
P 422 line −8	Replace first 'cluster' by 'clusters'.
P 433 line −1	Delete one 'the'.
P 438 line −6	Replace "grid-size. which" by "grid-size, which".
P 462	Rename Section 11.2.1.1 as "Characterisation of Strategies and Problem Instances".
P 462	Add the following paragraph to Section 11.2.1.1: "Problem design (via templates, or more refined bad-case examples) needs to be structurally *catalogued*, if possible. Also, the concept of fairness, methods for 'quickly' estimating the value of a game, and playing against a 'capricious' game designer need to be investigated. It is also necessary to further distinguish between inherently difficult problems, and those which are difficult for the solution strategies."

Bibliography

[12] BALL, M. O. Allocation/routing: models and algorithms. In *Vehicle Routing: Methods and Studies*, B. L. Golden and A. A. Assad, Eds. Elsevier Science, New York, 1988, pp. 199–221.

[51] DELL'AMICO, M., MAFFIOLI, F., AND VÄRBRAND, P. On prize-collecting tours and the asymmetric travelling salesman problem. *International Transactions in Operational Research 2* (1995), 297–308.

[202] VOLGENANT, T., AND JONKER, R. On some generalizations of the travelling salesman problem. *Journal of the Operational Research Society 38*, 11 (1987), 1073–1079.

[207] WINSTON, W. L. *Operations Research: Applications and Algorithms*, 3rd ed. Duxbury Press, Belmont, California, 1994.

Glossary of Symbols

The Players

$\mathcal{A}$, $\mathcal{B}$	The two specific players.	39
$\mathcal{C}$	A third specific player.	467
$\mathcal{X}$, $\mathcal{Y}$	Generic players, not specifically stating which is player $\mathcal{A}$ or which is player $\mathcal{B}$.	45
$(x_A, y_A), (x_B, y_B)$	The initial location of the players.	39

Prizes, Clusters and Families

$V = \{1, 2, \ldots, n\}$	The set of all prizes.	39
(x_i, y_i)	The location of prize i.	39
v_i	The value of prize i.	39
$[ci]$	A cluster, elements are prizes $j \in [ci]$.	211
$\eta_{[ci]}$	Required PCTSP value for cluster $[ci]$.	218
$\mathcal{C}$	A clustering, elements are clusters $[ci] \in \mathcal{C}$.	211
$\mathcal{F}$	A family (also a clustering).	216
$\mathbb{F}$	Set of families, elements are families $\mathcal{F} \in \mathbb{F}$.	216

The hierarchy of membership is $j \in [ci] = Q \in \mathcal{Q} \in \mathbb{Q}$.

Distances and Times

λ	Overall deadline.	39
Δ	Step size.	45
d_{ij}	Distance between prize i_1 and prize i_2.	46
d_{Xj}	Distance from player $\mathcal{X}$'s current location to prize j.	46
$D_{[ci][cj]}$	Distance between clusters.	212
$d_{jC_{[ci]}}$	Distance between prize j and the centroid of cluster $[ci]$.	212
τ_{Aj}	Earliest arrival time of player $\mathcal{A}$ at prize j.	149
τ_{Bj}	Earliest arrival time of player $\mathcal{B}$ at prize j.	149

Problem Instances

$\wp$	CPCP problem instance.	59
$P : n\ell\ell vab\lambda$	Prize class (P-class) of problem instances.	372
$C : m\ell\ell vs\kappa ab\lambda$	Cluster class (C-class) of problem instances.	375
$D : hcbssa$	Density class (D-class) of problem instances.	381

Player Strategies

$\mathbb{S}$	Set of player strategies.	381
$\mathbb{S}_{\infty}$	Infinite set of all possible player strategies.	381
$\mathbb{S}_{A\infty}$	Infinite set of all possible strategies for player $\mathcal{A}$ for the two prize CPCP.	122
$\mathbb{S}_{B\infty}$	Infinite set of all possible strategies for player $\mathcal{B}$ for the two prize CPCP.	122
a, b	Individual player strategies.	122

Game Values

$\Gamma_A(\wp)$	Maximum value guaranteed to player $\mathcal{A}$.	59
$\Gamma_B(\wp)$	Maximum value guaranteed to player $\mathcal{B}$.	59
$\Omega(\wp)$	Cooperative value.	118
$\varkappa_A(\wp; \mathcal{A} \sim \mathsf{a}, \mathcal{B} \sim \mathsf{b})$	Score for player $\mathcal{A}$.	401
$\varkappa_B(\wp; \mathcal{A} \sim \mathsf{a}, \mathcal{B} \sim \mathsf{b})$	Score for player $\mathcal{B}$.	401
$\varkappa_A(\mathbb{P}; \mathcal{A} \sim \mathsf{a}, \mathcal{B} \sim \mathbb{S})$	Effectiveness: either MIN-MIN, MIN-MEAN or MEAN-MEAN.	401
$\varkappa^{\diamond}(\wp)$	Overall problem MAXIMIN score.	402
$\Xi(\wp; \mathcal{A} \sim \mathsf{a}, \mathcal{B} \sim \mathsf{b})$	Number of steps.	402
$\tau_A(\wp; \mathcal{A} \sim \mathsf{a}, \mathcal{B} \sim \mathsf{b})$	Processor time.	402
$\tau_B(\wp; \mathcal{A} \sim \mathsf{a}, \mathcal{B} \sim \mathsf{b})$	Processor time.	402
$\xi(\wp)$	Difficulty of problem instance $\wp$.	402
$\bar{\xi}(\mathbb{P})$	Average difficulty of a problem instance class $\mathbb{P}$.	402
$\upsilon_A(\wp; \mathcal{A} \sim \mathsf{a}, \mathcal{B} \sim \mathsf{b})$	Dynamic simulation battle value to player $\mathcal{A}$.	381
$\upsilon_B(\wp; \mathcal{A} \sim \mathsf{a}, \mathcal{B} \sim \mathsf{b})$	Dynamic simulation battle value to player $\mathcal{B}$.	381
$\upsilon_A^{*}(\wp)$, $\upsilon_B^{*}(\wp)$	Nash equilibrium value of the problem instance.	381
$\upsilon_A^{\sharp}(\wp)$, $\upsilon_B^{\sharp}(\wp)$	Infinite maximin value of the problem instance.	381
$\upsilon_A^{\diamond}(\wp)$, $\upsilon_B^{\diamond}(\wp)$	Computational maximin value of the problem instance.	385

$v^*(\wp)$, $v^H(\wp)$	Optimal and heuristic value of a solution to a combinatorial optimization problem $\wp$.	390
ρ_H	Worst case performance of a heuristic H on a combinatorial optimization problem.	390
$\xi(\wp)$	Difficulty of problem instance $\wp$.	392

Paths, Game Trees and Branch and Bound Trees

j	A game tree node.	155
i	A branch and bound tree node.	205
$\Gamma_{\mathcal{A}}(\mathsf{j})$	The guarantee value for player $\mathcal{A}$ corresponding to game tree node j.	160
$\Gamma_{\mathcal{B}}(\mathsf{j})$	The guarantee value for player $\mathcal{B}$ corresponding to game tree node j.	160
$\Omega(\mathsf{j})$	The cooperative value corresponding to game tree node j.	160
P	Planning subpath.	72
P_A	Planning path for player $\mathcal{A}$.	62
P_B	Planning path for player $\mathcal{B}$.	61
$v_A(P_A, P_B)$	The value of prize on subpath P_A claimed outright by player $\mathcal{A}$ plus half the value of those prizes on P_A shared with player $\mathcal{B}$ on subpath P_B.	155

Step Planning

$\mathcal{X} \multimap \boldsymbol{i}$	Player $\mathcal{X}$ moves one step towards prize $\boldsymbol{i}$.	92
$\mathcal{X} \multimap X$	Player $\mathcal{X}$ moves directly to location X.	92
$\mathcal{X} \rhd \boldsymbol{i}$	The 'look through' scenario that player $\mathcal{X}$ is committed to travelling all the way to prize $\boldsymbol{i}$.	92
$\mathcal{X} \rhd (\boldsymbol{i}_1 \to \boldsymbol{i}_2)$	The 'look through' scenario that player $\mathcal{X}$ is committed to travelling all the way to prize $\boldsymbol{i}_1$ then all the way to prize $\boldsymbol{i}_2$.	97
$\mathcal{X} \rhd (\boldsymbol{i}_1 \to \boldsymbol{i}_2 \to \boldsymbol{i}_3)$	The 'look through' scenario that player $\mathcal{X}$ is committed to travelling all the way to prize $\boldsymbol{i}_1$ then all the way to prize $\boldsymbol{i}_2$ then all the way to prize $\boldsymbol{i}_3$.	103

$\mathcal{X} \rhd \{\boldsymbol{i}_1, \boldsymbol{i}_2\}$	The 'look through' scenario that player $\mathcal{X}$ is committed to travelling all the way to at least one of prizes $\boldsymbol{i}_1$ and $\boldsymbol{i}_2$.	98

Tactical Planning

Q	Prizes remaining unclaimed.	49
Q_A, Q_B	Prizes remaining and accessible to each player.	147
P_A, P_B	Planning paths for each player.	148
t	Projected time stamp.	148
t_A, t_B	Projected time stamps.	168
$\mathcal{L}_A, \mathcal{L}_B$	Lead prizes for each player.	169
$\mathcal{D}_A, \mathcal{D}_B$	Direct lead prizes for each player.	169
$\mathcal{R}_A, \mathcal{R}_B$	Follow prizes for each player.	169
$\mathcal{F}_A, \mathcal{F}_B$	Follow pairs for each player.	170
$\odot$	Probe.	148
$\mathcal{X} \to P_X \odot x$	Probe.	148
$\oplus$	Commitment.	169
$\mathcal{X} \to P_X \oplus x$	Commitment.	169
W	Window scenario and corresponding feasibility window.	170
$\mathcal{X} \rhd (W \to \{\boldsymbol{i}_1, \boldsymbol{i}_2\})$	The 'look through' scenario that player $\mathcal{X}$ is committed to travelling all the way to at least one of prizes $\boldsymbol{i}_1$ and $\boldsymbol{i}_2$ via feasibility window W.	171

Strategic Planning

FF	Final family requirement enforced.	219
$\mathbb{Q}_A, \mathbb{Q}_B$	Families remaining and accessible to each player.	220
$\mathcal{Q}_A, \mathcal{Q}_B$	Clusters remaining and accessible to each player.	220
$\mathcal{S}_{\mathcal{X}}$	Set of target-clusters of player $\mathcal{X}$.	220
$\mathbb{P}_A, \mathbb{P}_B$	Cluster planning paths.	230
$\mathbf{W}$	Cluster window scenario and corresponding cluster window feasibility constraints.	257

$\mathcal{X} \rhd [ci]$	The 'look through' scenario that player $\mathcal{X}$ is committed to travelling all the way to some prize in cluster $[ci]$.	231
$\mathcal{B} \rhd \{[cy_1], [cy_2]\}$	The 'look through' scenario that player $\mathcal{B}$ is committed to travelling all the way to at least one prize from cluster $[cy_1]$ or cluster $[cy_2]$.	256
$\mathcal{B} \rhd ([cy_0] \to \{[cy_1], [cy_2]\})$	The 'look through' scenario that player $\mathcal{B}$ is committed to travelling all the way to at least one of prize from cluster $[cy_0]$ and then travelling all the way to at least one prize from cluster $[cy_1]$ or cluster $[cy_2]$.	257
$\mathcal{A} \to \mathbb{P}_A \oplus [cx_0] \rhd [cx_1]$	Player $\mathcal{A}$ moves through cluster $[cx_0]$ while committed to cluster $[cx_1]$ as the next look-through cluster.	238
$\mathcal{B} \to \mathbb{P}_B \rhd \emptyset$	Player $\mathcal{B}$ has no look-through commitment.	243
$\mathcal{B} \to \mathbb{P}_B \oplus [cx_0] \rhd \emptyset$	Player $\mathcal{B}$ moves through cluster $[cx_0]$ and has no further look-through commitment.	243
$\mathcal{B} \to \mathbb{P}_B \rhd [cx_0]$	Player $\mathcal{B}$ is committed to cluster $[cx_0]$ as the next look-through cluster.	253

Grid Planning

$\mathbb{G}_A, \mathbb{G}_B$	Grid planning paths.	344
$\mathcal{A} \to \mathbb{G}_A \oplus_D (i, j)$	Commitment to grid cell (i, j) via the intra-cell-direct-path through the current $\mathcal{A}$-grid-cell.	344
$\mathcal{A} \to \mathbb{G}_A \oplus_H (i, j)$	Commitment to grid cell (i, j) via the intra-cell-harvest-path through the current $\mathcal{A}$-grid-cell.	345
$\mathcal{A} \to \mathbb{G}_A \oplus_P (x, y)$	Commitment to grid cell (i,j) carrying last-direct, last-harvest and all-direct paths via the current $\mathcal{A}$-grid-cell.	348

Abstract

Operations Research studies a wide range of problems, including long-term, strategic, business planning and short-term, operational, logistical planning. Long-term business decisions revolve around the market demand for goods or services, whereas logistics focuses on efficient scheduling of production and distribution. However, vehicle routing and scheduling problems in a dynamic environment require short-term, operational planning in conjunction with computationally expensive, short-term tactical considerations.

This thesis investigates a model of competition in the distribution of goods to customers, in which a number of independent carriers compete to deliver goods to a fixed set of customers. Assuming that the price and quality of the goods are consistent, each customer is indifferent towards which carrier actually delivers the required goods, but will only accept delivery from the first to arrive at their location. The main source of uncertainty is planning for competition against other independent carriers.

Firstly, we consider the basic elements of competition vehicle routing and scheduling problems, and propose a Reference Model for Competition Routing Problems, synthesising the literature from vehicle routing and game theory. The general problem involves a number of independent decision makers, each representing a carrier company with a private fleet of vehicles, and a fixed set of customers to be serviced. We also formulate the Competitive Prize Collection Problem (CPCP), involving two independent decision makers with one vehicle each. The CPCP encapsulates the core elements of competition within a two player version of the Prize Collecting Travelling Salesman Problem.

Secondly, we consider which strategic, tactical, and operational planning elements are important in the design of strategies for effective performance on the CPCP. We propose a Strategic Planning Architecture (SPA), i.e., a strategy framework based on hierarchical planning at nested planning horizons. This incorporates strategic and tactical planning engines based on modelling the decision problem at each planning horizon as a multiple

stage game. Dynamic monitoring processes match these strategic plans to the predicted and observed movements of the opponent. Strategies which implement the SPA are designed to cover a range of planning horizons and problem sizes.

A series of computational tournaments on problems of different sizes and characteristics suggests that strategies which address contingent planning, cognizance of opponent, and planning based on existing natural structure, are the most effective of those considered. In the process, benchmark sets of robust strategies, and challenging problem instances, are established against which the effectiveness of strategies may be evaluated.

The significant conclusion is that for small problems, strategic considerations are more effective than routing, but for large problems, routing considerations are more effective than strategic. Problems in between require a balance between strategy, response, and routing considerations. Routing only is not sufficient; response requires good strategic information. The CPCP remains a deceptively simple problem which is computationally demanding at all scales of planning, from small problems to large problems. There is considerable scope for the study of further strategies, especially those able to classify, learn from and adapt to, the observed behaviour of the opponent, and for extrapolating these results to a richer set of competition routing problems.

Acknowledgements

When you are a bear of very little brain, and you think of things, you find sometimes that a thing which seemed very thingish inside you is quite different when it gets out into the open and has other people looking at it.

— WINNIE THE POOH (A.A. MILNE)

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Finally, thanks must go to my speedy typist, and my dedicated C, UNIX, and MATLAB guru and LaTeXnician, for prompt and excellent technical assistance (that's me).

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