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EDEXCEL A LEVEL FURTHER MATHEMATICS: QUESTIONS BY TOPIC

Allocation Problems (2)

Decision Mathematics 2 · Topic 2

6 questions · 47 marks · Mark schemes included

Pearson Edexcel A Level Further Mathematics (9FM0), June 2019 - June 2025

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HOW TO USE THIS BOOKLET

Questions are grouped by specification sub-topic and run from the lowest mark tariff to the highest within each one.

Click any row below to jump straight to that sub-topic or question.

On every question page, click ANSWER in the top-right corner to jump to its mark scheme.

Diagrams, graphs, tables and data are printed exactly as they appeared in the original papers.

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QUESTIONS

6 questions · 47 marks · 2 sub-topics



SUB-TOPIC 2.1

THE HUNGARIAN ALGORITHM

Sub-topic 2.1 · 5 questions · 38 marks · lowest tariff first



1. Four workers, A, B, C and D, are to be assigned to four tasks, 1, 2, 3 and 4. Each task must be assigned to just one worker and each worker must do only one task.

The cost of assigning each worker to each task is shown in the table below.

The total cost is to be minimised.

	1	2	3	4
A	32	45	34	48
B	37	39	50	46
C	46	44	40	42
D	43	45	48	52

- (a) Reducing rows first, use the Hungarian algorithm to obtain an allocation that minimises the total cost. You must make your method clear and show the table after each stage.

(5)

- (b) State the minimum total cost.

(1)

(Total for Question 1 is 6 marks)



2. Four workers, Ted (T), Harold (H), James (J) and Margaret (M), are to be assigned to four tasks, 1, 2, 3 and 4. Each worker must be assigned to just one task and each task must be done by just one worker.

The profit, in pounds, resulting from allocating each worker to each task, is shown in the table below. The profit is to be maximised.

	1	2	3	4
T	103	97	74	80
H	201	155	145	155
J	111	80	77	92
M	203	188	137	184

- (a) Reducing rows first, use the Hungarian algorithm to obtain an allocation that maximises the total profit. You must make your method clear and show the table after each stage.

(6)

- (b) Determine the resulting total profit.

(1)

(Total for Question 2 is 7 marks)



1. Four workers, A, B, C and D, are to be assigned to four tasks, 1, 2, 3 and 4. Each worker must be assigned to exactly one task and each task must be done by exactly one worker.

Worker A cannot do task 3 and worker B cannot do task 4

The table below shows the profit, in pounds, that each worker would earn if assigned to each of the tasks.

	1	2	3	4
A	29	20	–	23
B	32	30	28	–
C	35	32	34	25
D	29	31	27	30

- (a) Reducing rows first, use the Hungarian algorithm to obtain an allocation that maximises the total profit. You must make your method clear and show the table after each stage.

(7)

- (b) Determine the resulting total profit.

(1)

(Total for Question 1 is 8 marks)



4. Four students, A, B, C and D, are to be allocated to four rounds, 1, 2, 3 and 4, in a competition. Each student is to take part in exactly one round and no two students may play in the same round.

Each student has been given an estimated score for each round. The estimated scores for each student are shown in the table below.

	1	2	3	4
A	34	20	18	15
B	49	31	12	34
C	48	27	23	26
D	52	45	42	42

- (a) Reducing rows first, use the Hungarian algorithm to obtain an allocation that maximises the total estimated score. You must make your method clear and show the table after each stage.

(7)

- (b) Find this total estimated score.

(1)

(Total for Question 4 is 8 marks)



2. Five workers, A, B, C, D and E, are available to complete four tasks, P, Q, R and S.

Each worker can be assigned to at most one task, and each task must be done by at most one worker.

Worker B cannot be assigned to task R.

The time, in minutes, that each worker takes to complete each task is shown in the table below.

	P	Q	R	S
A	25	32	43	28
B	41	37	–	38
C	43	35	37	39
D	40	33	37	41
E	37	38	43	40

The Hungarian algorithm is to be used to find an allocation that minimises the total time to complete all four tasks.

- (a) Explain how the table should be modified so that the Hungarian algorithm can be applied. (2)
- (b) Use the Hungarian algorithm to obtain an allocation that minimises the total time. (6)
- (c) Calculate the least total time to complete all four tasks. (1)

(Total for Question 2 is 9 marks)



SUB-TOPIC 2.2

ALLOCATION AS LINEAR PROGRAMMING

Sub-topic 2.2 · 1 question · 9 marks · lowest tariff first



4. Four workers, A, B, C and D, are to be assigned to four tasks, P, Q, R and S.

Each task must be assigned to just one worker and each worker can do only one task.

Worker B cannot be assigned to task Q and worker D cannot be assigned to task R.

The amount, in pounds, that each worker would earn when assigned to each task is shown in the table below.

	P	Q	R	S
A	65	72	69	75
B	71	–	68	65
C	70	69	73	77
D	73	70	–	71

The Hungarian algorithm can be used to find the maximum total amount that would be earned by the four workers.

- (a) (i) Explain how to modify the table so that the Hungarian algorithm could be applied.

- (ii) Modify the table as described in (a)(i).

(3)

- (b) Formulate the above situation as a linear programming problem. You must define the decision variables and make the objective function and constraints clear.

(6)

(Total for Question 4 is 9 marks)



MARK SCHEMES

official mark schemes



Question	Scheme	Marks	AOs
1(a)	Reduce rows $\begin{bmatrix} 0 & 13 & 2 & 16 \\ 0 & 2 & 13 & 9 \\ 6 & 4 & 0 & 2 \\ 0 & 2 & 5 & 9 \end{bmatrix}$ and then columns $\begin{bmatrix} 0 & 11 & 2 & 14 \\ 0 & 0 & 13 & 7 \\ 6 & 2 & 0 & 0 \\ 0 & 0 & 5 & 7 \end{bmatrix}$	M1 A1	2.1 1.1b
	Followed by $\begin{bmatrix} 0 & 11 & 0 & 12 \\ 0 & 0 & 11 & 5 \\ 8 & 4 & 0 & 0 \\ 0 & 0 & 3 & 5 \end{bmatrix}$	M1 A1ft	2.1 1.1b
	A – 3, B – 1, C – 4, D – 2 or A – 3, B – 2, C – 4, D – 1	A1ft	2.2a
		(5)	
(b)	158	B1	1.1b
		(1)	
(6 marks)			
Notes:			
(a) M1: simplifying the initial matrix by reducing rows and then columns. (Allow up to 2 independent slips). A1: CAO M1: develop an improved solution – need to see one double covered +e; one uncovered –e; and one single covered unchanged. 3 lines needed to 4 lines needed (lines may be implied). If lines are drawn they must be correct. A1ft: CAO following on from row and column reduction final table. (f/t from previous table with no further slips). A1ft: correct allocation ft their optimal table (both previous M marks must have been awarded in (a)) (Must be fully written. Do not accept just indicated on zeros on final matrix). (b)B1: CAO – solution of original problem			

Question	Scheme	Marks	AOs
2(a)	Reduce rows $\begin{bmatrix} 0 & 31 & 34 & 19 \\ 0 & 15 & 66 & 19 \end{bmatrix}$ and then columns $\begin{bmatrix} 0 & 0 & 0 & 4 \\ 0 & 40 & 27 & 27 \\ 0 & 25 & 5 & 0 \\ 0 & 9 & 37 & 0 \end{bmatrix}$ followed by $\begin{bmatrix} 5 & 0 & 0 & 9 \\ 0 & 35 & 22 & 27 \\ 0 & 20 & 0 & 0 \\ 0 & 4 & 32 & 0 \end{bmatrix}$	1M1 1A1ft 2M1 2A1ft	2.1 1.1b 2.1 1.1b
	T – 2, H – 1, J – 3, M – 4	3A1	2.2a
		(6)	
(b)	(£)559	1B1	1.1b
		(1)	
(7 marks)			
Notes:			
(a) 1B1: CAO 1M1: simplifying the initial matrix by reducing rows and then columns. Allow no more than a single error in row reduction together with no more than a single error in column reduction. May combine the two stages of converting from maximum to a minimum problem and row reduction which is acceptable. 1A1ft: CAO following on from their earlier conversion to maximising. If 1B1 awarded, the result of row and column reduction must be as in the main scheme. If 1B0 awarded, then row and column reduction must fit correctly from their attempt to convert to maximisation problem. 2M1: develops an improved solution – need to see one double covered +e; one uncovered –e; and one single covered unchanged. 3 lines needed to 4 lines needed 2A1ft: Improved solution following on from their previous table 3A1: CSO Correct allocation. Must have gained all previous marks in the question. (b) 1B1: CAO – solution of original problem (ignore units lack of or incorrect units)			



SC: Minimising

After row reduction $\begin{bmatrix} 29 & 23 & 0 & 6 \\ 56 & 10 & 0 & 10 \\ 34 & 3 & 0 & 15 \\ 66 & 51 & 0 & 47 \end{bmatrix}$ and then after column reduction $\begin{bmatrix} 0 & 20 & 0 & 0 \\ 27 & 7 & 0 & 4 \\ 5 & 0 & 0 & 9 \\ 37 & 48 & 0 & 41 \end{bmatrix}$

After augmentation $\begin{bmatrix} 0 & 20 & 4 & 0 \\ 23 & 3 & 0 & 0 \\ 5 & 0 & 4 & 9 \\ 33 & 44 & 0 & 37 \end{bmatrix}$ or $\begin{bmatrix} 0 & 24 & 4 & 0 \\ 23 & 7 & 0 & 0 \\ 1 & 0 & 0 & 5 \\ 33 & 48 & 0 & 37 \end{bmatrix}$

Scores B0 M1A0 M1A1(ft)A0 B0 (So 3 marks max)

1B0: No Minimisation

1M1: simplifying the initial matrix by reducing rows and then columns – all values ‘correct’

1A0: Must be maximising.

2M1: develops an improved solution – need to see one double covered +e; one uncovered –e; and one single covered unchanged. 3 lines needed to 4 lines needed

2A1ft: Improved solution following on from their previous table

3A0: CSO

1B0: Must be maximising



Question	Scheme	Marks	AOs
1(a)	Subtracting each entry from a constant value ≥ 35 to convert from maximisation problem to minimisation	M1	1.1b
	Add a sufficiently large number (> 15) to cells A3 and B4 e.g. $\begin{bmatrix} 6 & 15 & 100 & 12 \\ 3 & 5 & 7 & 100 \\ 0 & 3 & 1 & 10 \\ 6 & 4 & 8 & 5 \end{bmatrix}$	B1	1.1b
	Reduce rows $\begin{bmatrix} 0 & 9 & 94 & 6 \\ 0 & 2 & 4 & 97 \\ 0 & 3 & 1 & 10 \\ 2 & 0 & 4 & 1 \end{bmatrix}$ and then columns $\begin{bmatrix} 0 & 9 & 93 & 5 \\ 0 & 2 & 3 & 96 \\ 0 & 3 & 0 & 9 \\ 2 & 0 & 3 & 0 \end{bmatrix}$	M1 A1ft	2.1 1.1b
	followed by $\begin{bmatrix} 0 & 7 & 93 & 3 \\ 0 & 0 & 3 & 94 \\ 0 & 1 & 0 & 7 \\ 4 & 0 & 5 & 0 \end{bmatrix}$ or $\begin{bmatrix} 0 & 7 & 91 & 3 \\ 0 & 0 & 1 & 94 \\ 2 & 3 & 0 & 9 \\ 4 & 0 & 3 & 0 \end{bmatrix}$	M1 A1ft	2.1 1.1b
	A – 1, B – 2, C – 3, D – 4	B1ft	1.1b
		(7)	
(b)	£123	B1	1.1b
		(1)	
(8 marks)			
Notes:			
(a) M1: convert from maximisation to minimisation (allow at most two errors) B1: adding a large number (at least 16) to cells A3 and B4 M1: simplifying the initial matrix by reducing rows and then columns A1ft: cao following on from their earlier subtraction M1: develop an improved solution – need to see one double covered +e; one uncovered –e; and one single covered unchanged. 3 lines needed to 4 lines needed A1ft: cao following on from row and column reduction final table (b) B1ft: correct allocation ft their optimal table (all previous M marks must have been awarded in (a)) B1: cao – solution of original problem			





Question	Scheme	Marks	AOs
4(a)	Since maximising, subtract all elements from some value ≥ 52 e.g. $\begin{bmatrix} 18 & 32 & 34 & 37 \\ 3 & 21 & 40 & 18 \\ 4 & 25 & 29 & 26 \\ 0 & 7 & 10 & 10 \end{bmatrix}$	B1	1.1b
	Reduce rows $\begin{bmatrix} 0 & 14 & 16 & 19 \\ 0 & 18 & 37 & 15 \\ 0 & 21 & 25 & 22 \\ 0 & 7 & 10 & 10 \end{bmatrix}$ and then columns $\begin{bmatrix} 0 & 7 & 6 & 9 \\ 0 & 11 & 27 & 5 \\ 0 & 14 & 15 & 12 \\ 0 & 0 & 0 & 0 \end{bmatrix}$	M1 A1	2.1 1.1b
	$\begin{bmatrix} 0 & 2 & 1 & 4 \\ 0 & 6 & 22 & 0 \\ 0 & 9 & 10 & 7 \\ 5 & 0 & 0 & 0 \end{bmatrix}$ followed by $\begin{bmatrix} 0 & 1 & 0 & 3 \\ 1 & 6 & 22 & 0 \\ 0 & 8 & 9 & 6 \\ 6 & 0 & 0 & 0 \end{bmatrix}$ or $\begin{bmatrix} 0 & 1 & 0 & 4 \\ 0 & 5 & 21 & 0 \\ 0 & 8 & 9 & 7 \\ 6 & 0 & 0 & 1 \end{bmatrix}$	M1 A1ft A1	2.1 1.1b 1.1b
	Optimal allocation is A = 3, B = 4, C = 1, D = 2	A1ft	2.2a
		(7)	
(b)	Total score = $18 + 34 + 48 + 45 = 145$	B1	2.2a
		(1)	
(8 marks)			
Notes:			
(a) B1: converting correctly from a minimisation to maximisation M1: simplifying the initial matrix by reducing rows and then columns (allow up to 2 independent slips) A1: CAO M1: develop an improved solution – need to see one double covered +e; one uncovered –e; and one single covered unchanged. 2 lines needed to 3 lines needed (lines may be implied). If lines are drawn they must be correct. A1ft: CAO following on from row and column reduction from previous table (f/t from previous table with no further slips) A1: CSO on final table (so must have scored all previous marks) A1ft: correct allocation ft their optimal table (both previous M marks must have been awarded in (a)) (Must be fully written. Do not accept just indicated on zeroes on final matrix) (b) B1: CAO – solution of original problem (both previous M marks must have been awarded)			

Question	Scheme	Marks	AOs
4(a)	Special Case – minimisation – max 4/8	B0	
	Reduce rows $\begin{bmatrix} 19 & 5 & 3 & 0 \\ 37 & 19 & 0 & 22 \\ 25 & 4 & 0 & 3 \\ 10 & 3 & 0 & 0 \end{bmatrix}$ and then columns $\begin{bmatrix} 9 & 2 & 3 & 0 \\ 27 & 16 & 0 & 22 \\ 15 & 1 & 0 & 3 \\ 0 & 0 & 0 & 0 \end{bmatrix}$	M1 A1	
	followed by $\begin{bmatrix} 8 & 1 & 3 & 0 \\ 26 & 15 & 0 & 22 \\ 14 & 0 & 0 & 3 \\ 0 & 0 & 1 & 1 \end{bmatrix}$ or $\begin{bmatrix} 9 & 2 & 4 & 0 \\ 26 & 15 & 0 & 21 \\ 14 & 0 & 0 & 2 \\ 0 & 0 & 1 & 0 \end{bmatrix}$	M1 A1 A0	
	Optimal allocation is	A0	
		(7)	
(b)	Total score	B0	
		(1)	
(8 marks)			
Notes:			
(a) B0: no conversion M1: simplifying the initial matrix by reducing rows and then columns (allow up to 2 independent slips) A1: CAO M1: develop an improved solution – need to see one double covered +e; one uncovered –e; and one single covered unchanged. 3 lines needed to 4 lines needed (lines may be implied). If lines are drawn they must be correct. A1: CAO No further marks awarded			

Question	Scheme	Marks	AOs
2(a)	Add an additional dummy column with equal values (e.g. 0) to create a square array	B1	3.5c
	Input a suitable large number (e.g. 100 but > 43) in cell BR	B1	1.1b
		(2)	
(b)	e.g. $\begin{pmatrix} & P & Q & R & S & X \\ A & 25 & 32 & 43 & 28 & 0 \\ B & 41 & 37 & 100 & 38 & 0 \\ C & 43 & 35 & 37 & 39 & 0 \\ D & 40 & 33 & 37 & 41 & 0 \\ E & 37 & 38 & 43 & 40 & 0 \end{pmatrix}$	B1	1.1b
	Reducing (rows and) columns gives		
	$\begin{pmatrix} & P & Q & R & S & X \\ A & 0 & 0 & 6 & 0 & 0 \\ B & 16 & 5 & 63 & 10 & 0 \\ C & 18 & 3 & 0 & 11 & 0 \\ D & 15 & 1 & 0 & 13 & 0 \\ E & 12 & 6 & 6 & 12 & 0 \end{pmatrix}$	M1	1.1b
	Three lines required to cover the zeros hence solution is not optimal (augment by 1)		
	$\begin{pmatrix} & P & Q & R & S & X \\ A & 0 & 0 & 7 & 0 & 1 \\ B & 15 & 4 & 63 & 9 & 0 \\ C & 17 & 2 & 0 & 10 & 0 \\ D & 14 & 0 & 0 & 12 & 0 \\ E & 11 & 5 & 6 & 11 & 0 \end{pmatrix}$	M1	1.1b
	Four lines (e.g. A, Q, R and X) required to cover the zeros hence solution is not optimal (augment by 9)		
	e.g. $\begin{pmatrix} & P & Q & R & S & X \\ A & 0 & 9 & 16 & 0 & 10 \\ B & 6 & 4 & 63 & 0 & 0 \\ C & 8 & 2 & 0 & 1 & 0 \\ D & 5 & 0 & 0 & 3 & 0 \\ E & 2 & 5 & 6 & 2 & 0 \end{pmatrix}$	M1 A1	1.1b 1.1b
	Five lines required to cover the zeros hence solution is optimal		
	Allocation: A to P, B to S, C to R, and D to Q (E does no task)	A1ft	2.2a
		(6)	

(c)	133 (mins)	B1	1.1b
		(1)	
(9 marks)			
Notes for Question 2			
(a) B1: Explain the need to add a dummy column to create a square array B1: Input a large value in cell BR (b) See Example for large number in dummy B1: Mark awarded when both steps complete (addition of extra column with 0s in every cell and large value in cell BR) (Note may be implied by sight of table with (rows and) columns reduced) M1: Simplifying the initial matrix by reducing columns M1: Develop an improved solution – need to see one double covered +e; one uncovered –e; and one single covered unchanged. 3 lines needed to 4 lines needed M1: Develop an improved solution – need to see one double covered +e; one uncovered –e; and one single covered unchanged. 4 lines needed to 5 lines needed A1: CSO on final table (so must have scored all previous marks in this part with no errors) A1ft: Deduction of the correct allocations following through their 5 line final table (must have scored all previous M marks) (c) B1: CAO ('mins' not required)			



Alternatives for **(b)** – after 4 lines may possibly see another 4 lines before 5 lines or two further 4 lines before 5 lines

The 3rd M mark in this case is only awarded when 5 lines are needed

	P	Q	R	S	X
A	0	0	7	0	1
B	15	4	63	9	0
C	17	2	0	10	0
D	14	0	0	12	0
E	11	5	6	11	0

	P	Q	R	S	X
A	0	0	7	0	1
B	15	4	63	9	0
C	17	2	0	10	0
D	14	0	0	12	0
E	11	5	6	11	0

	P	Q	R	S	X
A	0	0	7	0	5
B	11	0	59	5	0
C	17	2	0	10	4
D	14	0	0	12	4
E	7	1	2	7	0

	P	Q	R	S	X
A	0	0	9	0	3
B	13	2	63	7	0
C	15	0	0	8	0
D	14	0	2	12	2
E	9	3	6	9	0

	P	Q	R	S	X
A	0	5	12	0	10
B	6	0	59	0	0
C	12	2	0	5	4
D	9	0	0	7	4
E	2	1	2	2	0

	P	Q	R	S	X
A	0	0	9	0	5
B	11	0	61	5	0
C	15	0	0	8	2
D	14	0	2	12	4
E	7	1	4	7	0

	P	Q	R	S	X
A	0	5	14	0	10
B	6	0	61	0	0
C	10	0	0	3	2
D	9	0	2	7	4
E	2	1	4	2	0

Example – Large Number in Dummy – (b) B1 M1 M1 M1 A1 A1

	P	Q	R	S	X
A	25	32	43	28	100
B	41	37	100	38	100
C	43	35	37	39	100
D	40	33	37	41	100
E	37	38	43	40	100

	P	Q	R	S	X
A	0	7	18	3	75
B	4	0	63	1	63
C	8	0	2	4	65
D	7	0	4	8	67
E	0	1	6	3	63

	P	Q	R	S	X
A	0	7	16	2	12
B	4	0	61	0	0
C	8	0	0	3	2
D	7	0	2	7	4
E	0	1	4	2	0

Question	Scheme	Marks	AOs
4(a)	(i) Subtracting each entry from a constant value e.g. ≥ 77 to convert from maximisation problem to minimisation	B1	3.5c
	Add a sufficiently large number (> 12) to cells BQ and DR	B1	1.1b
	(ii) e.g. $\begin{bmatrix} 12 & 5 & 8 & 2 \\ 6 & 100 & 9 & 12 \\ 7 & 8 & 4 & 0 \\ 4 & 7 & 100 & 6 \end{bmatrix}$	B1	1.1b
		(3)	
(b)	Let x_{ij} be 0 or 1 $\begin{cases} 1 & \text{if worker } (i) \text{ does task } (j) \\ 0 & \text{otherwise} \end{cases}$	B1	3.3
	where $i \in \{A, B, C, D\}$ and $j \in \{P, Q, R, S\}$	B1	2.5
	minimise $12x_{AP} + 5x_{AQ} + 8x_{AR} + 2x_{AS} + 6x_{BP} + '100'x_{BQ} + 9x_{BR} + 12x_{BS} \\ + 7x_{CP} + 8x_{CQ} + 4x_{CR} + 4x_{DP} + 7x_{DQ} + '100'x_{DR} + 6x_{DS}$	M1 A1	3.3 1.1b
	Subject to $\sum x_{Aj}=1, \sum x_{Bj}=1, \sum x_{Cj}=1, \sum x_{Dj}=1$ $\sum x_{iP}=1, \sum x_{iQ}=1, \sum x_{iR}=1, \sum x_{iS}=1$	M1 A1	3.3 1.1b
		(6)	
(9 marks)			

Notes for Question 4

(a) **B1:** correct reasoning for how to convert from maximisation to minimisation

B1: adding a large number (at least 13) to cells BQ and DR

B1: CAO

(b) **B1:** defining x_{ij} correctly

B1: correct definition of the values that i and j can take

M1: Attempt at a 15 (or 16) term expression in terms of x (or their defined variable), coefficients ‘correct’, 2 ‘large’ values included, condone 2 slips. If more than 2 errors in (a) ft exactly their table for this mark only.

A1: CAO including ‘minimise’ (or equivalent 14 term expression with ‘maximise’)

M1: At least four equations, each in three or four variables, unit coefficients, equal to 1 Do not accept inequalities

A1: CAO (all eight equations)

$$\begin{array}{l}
 \text{Maximise} \quad 65x_{AP} + 72x_{AQ} + 69x_{AR} + 75x_{AS} \\
 \quad + 71x_{BP} \quad \quad + 68x_{BR} + 65x_{BS} \\
 \quad + 70x_{CP} + 69x_{CQ} + 73x_{CR} + 77x_{CS} \\
 \quad + 73x_{DP} + 70x_{DQ} \quad \quad + 71x_{DS}
 \end{array}$$

Note: if maximising they must not include a large number for BQ and DR, so only 14 terms

