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Examiners' report

FURTHER MATHEMATICS A

H245

For first teaching in 2017

Y544/01 Summer 2023 series

Version 1

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Contents

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Introduction

Our examiners' reports are produced to offer constructive feedback on candidates' performance in the examinations. They provide useful guidance for future candidates.

The reports will include a general commentary on candidates' performance, identify technical aspects examined in the questions and highlight good performance and where performance could be improved. A selection of candidate answers is also provided. The reports will also explain aspects which caused difficulty and why the difficulties arose, whether through a lack of knowledge, poor examination technique, or any other identifiable and explainable reason.

Where overall performance on a question/question part was considered good, with no particular areas to highlight, these questions have not been included in the report.

A full copy of the question paper and the mark scheme can be downloaded from OCR.

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Paper Y544/01 series overview

This is an option paper for Further Mathematics. It assesses Discrete Mathematics through graphs and networks, algorithms, linear programming and the application of these to problems including critical path analysis and game theory.

Candidates who did well on this paper generally:	Candidates who did less well on this paper generally:
• worked neatly and explained their working where appropriate • attempted all questions and gave responses that were appropriate for the number of marks available.	• did not read the questions carefully enough • worked in a muddled way and misread their own letters or numerical values • did not use algorithms given in the formulae booklet.

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Question 1 (a)

1 The table below shows the activities involved in a project together with the immediate predecessors and the duration of each activity.

Activity	Immediate predecessors	Duration (hours)
A	–	2
B	A	3
C	–	4
D	C	2
E	B, C	2
F	D, E	3
G	E	2
H	F, G	1

(a) Model the project using an activity network. **[3]**

This was usually done well. The project only needs two dummy activities but several candidates had extra dummy activities. A few did not have a single start or a single finish and several did not show the directions of the arcs (activities).

Only a small number of candidates used activity-on-node instead of activity-on-arc.

Question 1 (b)

(b) Determine the minimum project completion time. **[2]**

Most candidates were able to identify the minimum project completion time as being 11 hours, usually by carrying out a forward pass. Some candidates also used a backward pass and then justified the 11 hours by listing the critical path.

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Question 1 (c)

The start of activity C is delayed by 2 hours.

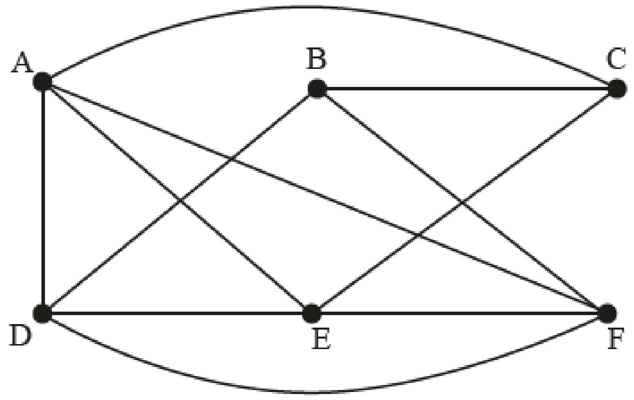
(c) Determine the minimum project completion time with this delay. **[2]**

Most candidates were able to identify that the minimum project completion time was now 12 hours, and several talked about there being a delay of 1 hour. Some found one or both of the new critical paths, both of which now involved activity C.

Candidates often said that 'C has 1 hour of float' when in fact C had 1 hour of float before but is now critical.

Question 2 (a)

2 A graph is shown below.



(a) Write down a cycle through all six vertices. **[1]**

This was usually correct. Most candidates wrote a suitable cycle, passing through every vertex once and finishing at the start vertex. Diagrams were not acceptable final solutions.

Question 2 (b)

(b) Write down a continuous route that uses every arc exactly once. **[2]**

Most candidates realised that the route needed to start at B and finish at C (or start at C and finish at B) having used every arc once. A few candidates gave a route that travelled through every vertex but did not use every arc.

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Question 2 (c)

(c) Use Kuratowski's theorem to show that the graph is **not** planar. **[2]**

Most candidates tried to find K3,3 as a subgraph and hence use Kuratowski to conclude that the graph is not planar. The two sets that form the bipartite graph are {A, B, E} and {C, D, F} with arcs AE and DF deleted.

Some candidates contracted BC to form K5 and then used Kuratowski as above. This was often the easier solution for this part but made the next part more difficult.

Question 2 (d)

(d) Show that the graph has thickness 2. **[3]**

Having shown that the graph is not planar means that it must have thickness of at least 2.

Constructing two planar subgraphs that between them cover the entire graph (with no duplication) shows that the thickness is at most 2, and hence that the thickness does equal 2.

It is helpful if the subgraphs are drawn without arcs crossing, so that it is obvious that they are planar.

The vertices of the subgraphs need to be labelled (A, B, C, …) and it needs to be evident which arcs are on which 'layer' if either subgraphs is not connected.

Quoting the fact that K3,3 (or K5) has thickness 2 was not appropriate as a solution to this part. Candidates needed to show the result, not deduce it from quotable facts.

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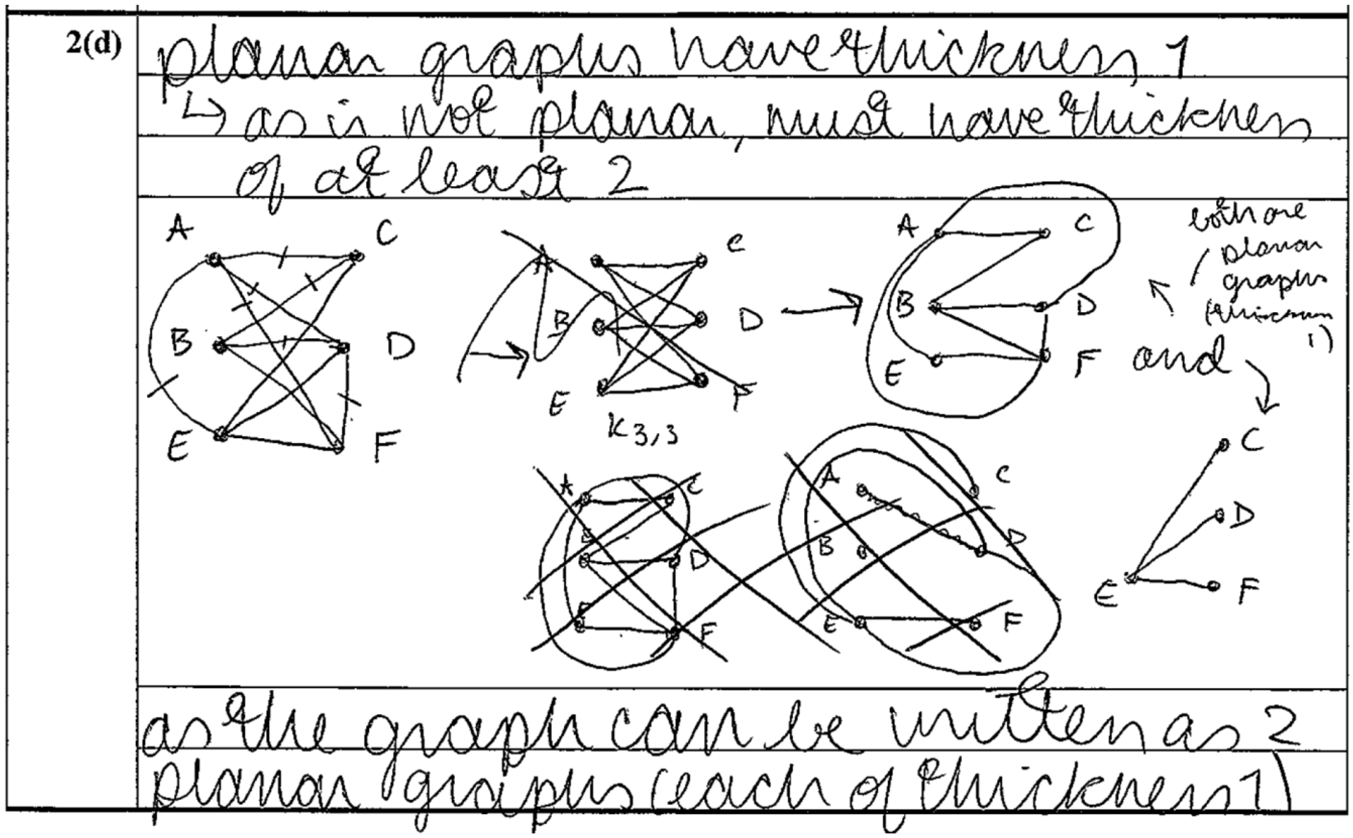
Exemplar 1


2(d) planar graphs have thickness 1
↳ as is not planar, must have thickness of at least 2

as the graph can be written as 2 planar graphs (each of thickness 1)

This candidate has said that as the graph is not planar it must have thickness at least 2.

They have then drawn two clearly planar labelled subgraphs. These collectively cover all the arcs in the original graph, however the arc EF has been repeated so the candidate loses the final mark.

The candidate's response did continue on a separate sheet where it said 'it must have a thickness of 2'. The conclusion would have been needed for full marks had the subgraphs been suitable.

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Question 3 (a)

3 An initial simplex tableau is given below.

P	x	y	z	s	t	RHS
1	-2	3	-1	0	0	0
0	5	-4	1	1	0	20
0	2	-1	0	0	1	6

(a) Carry out **two** iterations of the simplex algorithm, choosing the first pivot from the x column. **[4]**

Most candidates were able to carry out two iterations of the simplex algorithm.

The algorithm is given in the formulae booklet where step 1 starts with 'Choose a column with a negative entry in the objective row …'; this is why the question specified that the first pivot should be chosen from the *x* column.

Assessment for learning

If there are multiple columns with negative entries in the objective row and the question does not specify which should be chosen as the pivot then any of these columns may be used.

If there are no negative entries in the objective row then non-basis columns with 0 in the objective row may give degenerate cases (where the objective does not increase).

Assessment for learning

After each iteration there should be:

- a full set of basis columns (including P)
- no negative values in the RHS column
- the value of P (RHS of objective row) should have increased (or remained the same in a degenerate case).

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Question 3 (b)

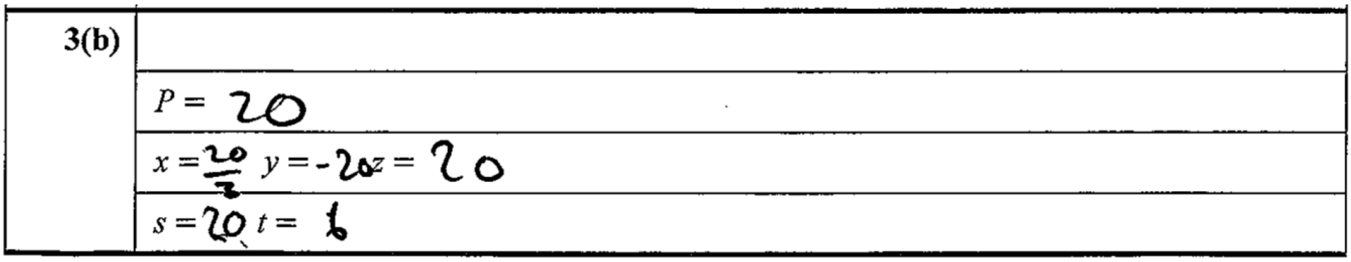
After three iterations the resulting tableau is as follows.

P	x	y	z	s	t	RHS
1	3	−1	0	1	0	20
0	5	−4	1	1	0	20
0	2	−1	0	0	1	6

(b) State the values of P, x, y, z, s and t that result from these three iterations. **[2]**

Many candidates were able to read off the six values correctly. Some candidates thought that *s* was also a basis variable and gave it the value 20.

Exemplar 2



3(b)	
	$P = 20$
	$x = \frac{20}{3}$ $y = -20$ $z = 20$
	$s = 20$ $t = 6$

This candidate has given the value of the basis variables correctly and scored B1.

For each basis column the value of the variable is found by reading down to the 1 and then across to the RHS column. This gives *P* = 20, *z* = 20 and *t* = 6.

Non-basis variables have the value 0, so *x*, *y* and *t* should be 0. The candidate seems to have used the objective row and calculated RHS divided by value in column for each of *x*, *y* and *s*.

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Question 3 (c)

(c) Explain why no further iterations are possible. **[2]**

Many candidates explained why no row was suitable as a pivot from the *y* column (all entries are negative but the pivot entry must be positive, we cannot pivot on 0 or a negative value). However fewer explained why *y* is the only potential pivot column.

Some said that the pivot must be from the *y* column because it has the most negative value in the objective row. While it is often the case that the column with the most negative value in the objective row will give the biggest improvement it is not necessarily the case, so candidates needed to explain that *y* was the only column with a negative value in the objective row.

Some candidates thought that the optimum had been achieved because 'there are no negative values in the objective row'. Although this is often the reason why no further iterations are possible it is not true here. A few candidates also considered the possibility of degenerate solutions, but these only arise when there is a 0 in the objective row that is not in a basis column.

Question 3 (d)

The initial simplex tableau is changed to the following, where k is a positive real value.

P	x	y	z	s	t	RHS
1	2	-3	1	0	0	0
0	5	k	1	1	0	20
0	2	-1	0	0	1	6

After one iteration of the simplex algorithm the value of P is 500.

(d) Deduce the value of k. **[4]**

Several candidates were able to find the value of *k* correctly. Candidates who used a tableau to show at least the pivot row often scored full marks, but those who used algebraic reasoning sometimes came unstuck and did not have a complete response.

Assessment for learning

'Deduce' is not one of the command words defined in the specification, but takes its ordinary English meaning 'to derive as a conclusion from something known'. Candidates should justify the steps of the mathematical reasoning similar to the detail shown on 'Determine' and 'Show that' questions.

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Question 4 (a)

4 The first 20 consecutive positive integers include the 8 prime numbers 2, 3, 5, 7, 11, 13, 17 and 19.

Emma randomly chooses 5 distinct numbers from the first 20 consecutive positive integers. The order in which Emma chooses the numbers does **not** matter.

(a) Calculate the number of possibilities in which Emma's 5 numbers include exactly 2 prime numbers and 3 non-prime numbers. **[2]**

There were several correct responses but there were some where candidates just wrote down every calculation or value that they thought might be relevant in the hope that something may have been correct.

Some candidates calculated ${}^{8}C_2 = 28$ and ${}^{12}C_3 = 220$ but then added them.

A few calculated 6160 but then divided it by ${}^{20}C_5$ to give a probability. On this specification combinatorial arguments will lead to integer solutions, not fractions.

Question 4 (b)

(b) Calculate the number of possibilities in which Emma's 5 numbers include at least 2 prime numbers. **[3]**

Again, there were several correct responses but there were some where candidates just wrote down calculations or values in the hope that they may have been relevant.

Most of the candidates who achieved 10752 got it by adding 3696, 840 and 56 to the value 6160 from part (a) but some used the total ${}^{20}C_5 = 15504$ and subtracted 3960 and 792.

Assessment for learning

Candidates should be encouraged to set out their working logically. Where multiple attempts, or some rough jottings have been shown, then a clear final solution should be given to make sure the examiner can clearly reward the intended work (refer to note (g) in the Subject Specific Marking Instructions of the mark scheme).

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Question 4 (c)

The pairs {3, 13} and {7, 17} each consist of numbers with a difference of exactly 10.

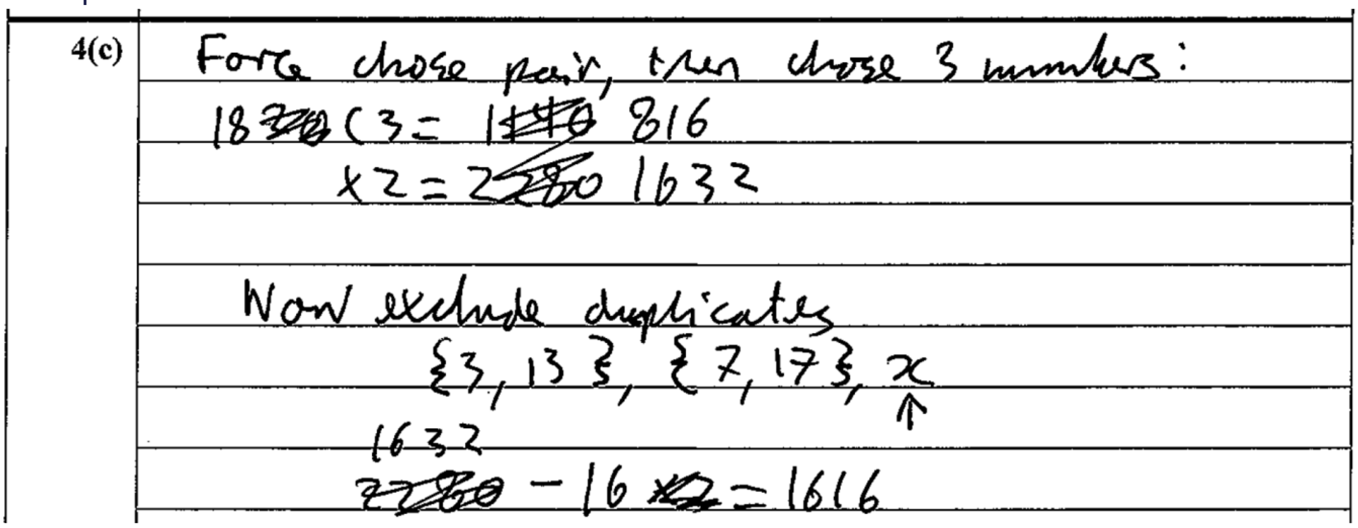
(c) Calculate the number of possibilities in which Emma's 5 numbers include at least one pair of prime numbers in which the difference between them is exactly 10. **[3]**

There were some excellent responses but there were several where candidates either appeared to not know what to do or did not attempt the question.

Some candidates had a good try at answering the question but overlooked all the cases that used exactly three of the values from {3, 13, 7, 17}, together with two other values.

Again, some candidates thought that they should be calculating a probability instead of the number of possibilities.

Exemplar 3


4(c)
Force chose pair, then chose 3 numbers:
$^{18}C_3$ = 816
×2 = 1632
Now exclude duplicates
{3, 13}, {7, 17}, x
1632
− 16 = 1616

This candidate has calculated that there are $^{18}C_3 = 816$ ways of choosing {3, 13} and three other values and similarly 816 ways of choosing {7, 17} and three others.

They have then used inclusion-exclusion to deduce the required answer.

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Question 4 (d)

A new set of 20 consecutive positive integers, each with at least two digits, is chosen.
This set of 20 numbers contains 5 prime numbers.

(d) Use the pigeonhole principle to show that there is at least one pair of these prime numbers for which the difference between them is exactly 10. **[2]**

A few of the candidates spent time worrying about numbers that were divisible by 3 and some gave reasoning based on a specific case, or assumed that the 20 consecutive positive integers were all less than 100.

Some candidates tried to construct pigeonholes corresponding to the differences between pairs of primes, but found that there were too many possibilities for the pigeonhole principle to be used (and the pigeons would have to have been pairs of primes, so we would not have known exactly how many pigeons were available).

Several candidates stated that the units digit of a two-digit prime must be odd and not equal to 5, and some of these went as far as saying that the set {1, 3, 5, 7} made up the pigeonholes. Most of these candidates then gave enough reasoning to achieve full marks.

Question 5 (a)

5 A list of 8 values is given below.

3 24 8 1 4 20 30 18

The list is to be sorted into increasing order using quick sort, as given in the Formulae Booklet.

(a) Carry out the first **two** passes of the sort. **[4]**

The quick sort algorithm is given in the formulae booklet.

Most candidates were able to carry out the required passes accurately. Some appeared to be using bubble sort or shuttle sort and some managed to misread their own numbers or lose a number between the two passes.

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Question 5 (b) (i)

A different list of 8 values is to be sorted into increasing order using quick sort, as given in the Formulae Booklet.

(b) (i) State the maximum number of passes that could be required. **[1]**

The formulae booklet states that sublists consisting of a single entry do not need to be considered, so, even in the worst case, there is no need for a final 8th pass.

Some candidates seemed to be counting comparisons or swaps, possibly for a bubble sort or shuttle sort.

Question 5 (b) (ii)

(ii) Find the minimum number of passes that could be required. **[2]**

Several candidates knew that the best case is when each pivot divides its sublist into two equal sized lists (or as near as possible to equal sized).

Some claimed that 4 passes were needed because of counting a final pass when the sublists are all of length 1, and some claimed that 4 passes were needed because they thought that dealing with the LHS and dealing with the RHS in pass 2 was two separate passes.

The first pass divides the list into sublists of length 3 and 4, with the pivot between them.

The second pass divides the sublist of length 3 into two sublists of length 1 with a pivot between them and divides the sublist of length 4 into sublists of length 1 and 2 with a pivot between them.

The only sublist that does not consist of a single entry is then the sublist of length 2 and this is dealt with in the third pass.

Question 5 (c)

The run-time for quick sort could be measured by counting the number of comparisons used.

In the worst case, the run time for quick sort is $O(n^2)$.

A computer takes at most 0.03 seconds to sort a list of 100 values into increasing order using quick sort.

(c) Calculate an estimate for the time taken, in the worst case, to sort a list of 500 values using quick sort. **[2]**

Most candidates were able to calculate the time as 0.75 seconds. Candidates should show their working, this is useful when it is difficult to know exactly what they are claiming as their answer (for example whether they have written 75 s or .75 s).

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Question 5 (d)

A list of n values (where $n > 10$) is to be sorted into increasing order using quick sort, as given in the Formulae Booklet.

(d) Explain why, in the **best** case, $n-3$ comparisons are used in the second pass. **[3]**

There was some misunderstanding over the fact that *n* was unknown but had already been chosen and that the phrase 'best case' referred to the entire process and not just the second pass.

The most successful responses were from candidates who made it clear that they understood that in the best case each sublist is split into roughly equal sized pieces, with a pivot between them. Candidates who dealt with the cases when *n* is odd and then separately dealt with the cases when *n* is even were often successful.

Question 6 (a)

6 A graph is shown in **Fig. 1.1.**
The graph is weighted to form the network represented by the weighted matrix in **Fig. 1.2**.
The weights represent distances in km.
A dash (-) means that there is no direct arc between that pair of vertices.

Fig. 1.1

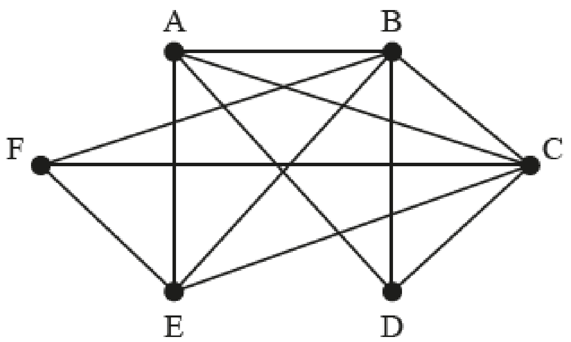

Fig. 1.2

	A	B	C	D	E	F
A	-	5	3	2	8	-
B	5	-	3	4	7	6
C	3	3	-	1	6	5
D	2	4	1	-	-	-
E	8	7	6	-	-	6
F	-	6	5	-	6	-

The shortest path from D to F has total weight 6.

(a) Write down a path from D to F of total weight 6. **[1]**

Most candidates were able to write down the path D – C – F correctly.

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Question 6 (b)

The total weight of the 12 arcs in the network is 56.

(b) Use the route inspection algorithm to calculate the total weight of the least weight route that covers every arc at least once, starting at vertex A. **[3]**

This is another method that is given in the formulae booklet.

Candidates should give enough working to show that they have followed the procedure correctly.

Question 6 (c)

(c) Determine the total weight of the least weight route that covers every arc at least once, starting at vertex B but finishing at any vertex. **[2]**

This part required adapting the solution to part (b), which gave the total weight of the least weight closed route, to deal with this case where the start and finish need not be at the same vertex.

Because B has an odd degree it is only necessary to duplicate one route between two of the odd vertices C, D and F. The shortest of these is CD = 1 and that gives 56+1 = 57. Alternatively, remove the largest weight route from B to one of C, D, F from the answer to part (b).

The command word 'determine' means that candidates need to justify any results found, including showing working where appropriate. Here this meant explaining why CD had been used (or why BF had been excluded).

Question 6 (d) (i)

Sasha wants to find a continuous route through every vertex, starting and finishing at vertex A, with the least total weight.

(d) **(i)** Use an appropriate algorithm to find a lower bound for the total weight of Sasha's route. **[4]**

The first step of the lower bound method involves finding a minimum spanning tree for a reduced network. Most candidates chose to remove vertex A and all arcs incident on A, although any vertex could be used.

Finding a minimum spanning tree means showing which arcs are included in the tree, this may be done by listing the arcs. Some candidates drew their tree, which was allowed even though the answer space was lined.

The second step involves finding the weight of the minimum spanning tree for the reduced network and connecting the missing vertex using two different arcs (of minimum total weight) to find the lower bound.

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Question 6 (d) (ii)

(ii) Use the Nearest Neighbour Algorithm, starting at vertex A, to find an upper bound for the total weight of Sasha's route. **[2]**

Most candidates were able to answer this correctly.

The route used needed to be written down as well as its total weight.

Question 6 (e)

Sasha decides to use the route A − B − F − E − C − D − A.

(e) Comment on the suitability of this route as a solution to Sasha's problem. **[2]**

Most candidates realised that this route did satisfy the criteria and had weight equal to the upper bound.

Some suggested that a shorter solution may exist but only a few addressed the practical issue of having to check every case to find out whether or not an improvement could be made.

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Question 7 (a) (i)

7 Player 1 and player 2 are playing a two-person zero-sum game.

In each round of the game the players each choose a strategy and simultaneously reveal their choice.

The number of points won in each round by player 1 for each combination of strategies is shown in the table below.

Each player is trying to maximise the number of points that they win.

		Player 2		
		A	B	C
Player 1	X	2	-3	-4
	Y	0	1	3
	Z	-2	2	4

(a) (i) Determine play-safe strategies for each player. **[3]**

Most candidates were able to work out the row minima and column maxima and use them to determine the play-safe strategies.

The command word 'Determine' means that candidates need to justify any results found, including showing working where appropriate. The row minima and column maxima needed to be shown (and be correct), together ideally with the row maximin and column minimax identified, as indication of the method used to find the play-safe strategies.

Question 7 (a) (ii)

(ii) Show that the game is **not** stable. **[1]**

There were many different approaches used here, most of which were valid. The briefest answer was to note that the play-safe strategies had different values ($0 \neq 2$) and hence the game is not stable.

Question 7 (b)

(b) Show that the number of strategies available to player 1 **cannot** be reduced by dominance. You must make it clear which values are being compared. **[2]**

Many sensible answers showing the comparisons made clearly and unambiguously and identifying which pair of strategies were being considered for dominance. Some candidates gave incomplete reasoning or did not make it clear which values were being compared. A few candidates showed that the strategies for player 2 could not be reduced.

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Question 7 (c)

Player 1 intends to make a random choice between strategies X, Y, Z, choosing strategy X with probability x, strategy Y with probability y and strategy Z with probability z.
Player 1 formulates the following LP problem so they can find the optimal values of x, y and z using the simplex algorithm.

Maximise $M = m - 4$
subject to $m \leqslant 6x + 4y + 2z$
$m \leqslant x + 5y + 6z$
$m \leqslant 7y + 8z$
$x + y + z \leqslant 1$
and $m \geqslant 0$, $x \geqslant 0$, $y \geqslant 0$, $z \geqslant 0$

(c) Explain how the inequality $m \leqslant 6x + 4y + 2z$ was formed. **[2]**

Most candidates appreciated that 4 had been added throughout the matrix, and often explained why.

Most candidates stated that the expression 6*x* + 4*v* + 2*z* is the amount, in the augmented matrix, that player 1 expects to win when player 2 chooses strategy A, some also explained the inequality.

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Question 7 (d)

The problem is solved by running the simplex algorithm on a computer.
The printout gives a solution in which $x+y=1$.
This means that the LP problem can be reduced to the following formulation.

Maximise $M=m-4$
subject to $m \leqslant 4+2x$
$m \leqslant 5-4x$
$m \leqslant 7-7x$
and $m \geqslant 0$, $x \geqslant 0$

(d) Solve this problem to find the optimal values of x, y and z and the corresponding value of the game to player 1. **[4]**

A few candidates tried to solve the problem using simplex, and very occasionally they were successful. However the intention was that the reduced problem, involving *m* and *x* (and *M*) could be solved graphically.

A sketch graph should be shown, the appropriate equations solved to give the values of *x*, y**,** z and *M* at the optimal solution, even if the details come from a graphical calculator.

Some of the sketches were barely acceptable, being drawn without the use of a ruler and occupying the smallest space imaginable.

Assessment for learning

Sketch graphs should be ruled and have labelled scales.

For graphical LP the horizontal axis should only extend from 0 to 1 and this should fill the width of the graph, the vertical axis should cover whatever range is necessary to show the extreme values of all the lines.

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