METIIB Paper 1 2024 CRIB

Question 1

a) i)

Best AM Process: Laser Powder Bed Fusion (LPBF)

- **Process Description**: The process involves the use of a laser to melt and fuse metallic powder. LPBF is typically used with alloys like steel, titanium, and Inconel.
  Good answers will include a graphics in their question.

  - **Justification**:
    - **Material Compatibility**: LPBF is highly compatible with titanium alloys, which are ideal for orthopaedic implants due to their strength and biocompatibility.
    - **Complex Geometries and Precision**: LPBF excels in producing complex, organic shapes and fine details, crucial for custom hip implants tailored to individual patient anatomy.
    - **Porous Structures**: LPBF can create controlled porous surfaces that are essential for bone ingrowth and osseointegration in orthopaedic implants.
    - **Biocompatibility and Sterility**: The process is conducive to maintaining the biocompatibility of titanium alloys and can achieve the sterility standards required for medical implants.

ii)

Post-Processing Considerations:

- **Surface Finishing**: Polishing or surface treatment may be required to achieve the smoothness required for a hip implant, minimizing wear and friction.
- **Heat Treatment**: This may be necessary to relieve internal stresses and optimize the mechanical properties of the titanium alloy.
- **Sterilisation**: The final implant must undergo a sterilisation process, such as autoclaving, to ensure it is safe for surgical use.

iii)

Cost and Production Time Implications:

- LPBF is well-suited for producing high-value, custom implants where each piece is unique. While the unit cost may be high compared to traditional manufacturing methods, the ability to customise each implant to the patient's specific anatomy provides significant value.
- The production time for a single implant is relatively short. However, the post-processing and quality assurance steps can extend the overall lead time.
- LBPF is not typically used for mass production due to its higher costs and slower production rate compared to traditional manufacturing. However, the complexity of this implant requirement renders this process route as the most capable and cost effective.

b)

Alternative Processes:

- **Electron Beam Melting (EBM)**:
  - **Pros**: Good for complex geometries and compatible with titanium alloys. Capable of creating porous structures.

        - **Cons**: Generally rougher surface finish compared to LPBF, and less widespread in the medical industry.
    - **Metal based Fused Deposition Modelling (FDM)**:
        - **Pros**: Can produce reasonably complex parts with low-cost metal infused polymer feed-stock.
        - **Cons**: Requires more extensive post-processing to achieve the desired material properties, leaves carbon residue in the metal part once it is fully sintered. Questionable biocompatibility.

c)

These are the areas for future development which could be discussed.

1. **Customisation and Personalisation**: One of the major advantages of AM is the ability to create customised and patient-specific implants. Future advancements will likely focus on increasing the level of personalisation, which can lead to better patient outcomes, quicker recovery times, and implants that are more compatible with the individual's anatomy.
2. **New Materials and Material Combinations**: Research in AM materials is rapidly evolving. The future may see the development of new biocompatible materials or composites that offer better integration with the human body, improved durability, and enhanced functional properties. The possibility of printing with multiple materials in a single implant could also open up new avenues for functionality and performance.
3. **Bioprinting and Tissue Engineering**: AM is expected to play a crucial role in the advancement of bioprinting, where biological materials are used to create tissue-like structures. This could revolutionise the field of regenerative medicine, enabling the creation of implants that not only replace damaged tissues but also promote regeneration and healing.
4. **Integration with Sensors and Drug Delivery Systems**: Future implants could be embedded with sensors to monitor their condition and the healing process, providing real-time data to healthcare providers. Additionally, implants with integrated drug delivery systems that release medication at the site of implantation could be developed, enhancing the treatment effectiveness.
5. **Improved Design Capabilities and Simulation Tools**: Advances in software and simulation tools will enable more complex and optimized implant designs. This includes the use of AI and machine learning for predicting implant performance and outcomes, leading to better design decisions and reduced risk of implant failure.
6. **Cost-Effectiveness and Accessibility**: As AM technologies mature and become more widespread, the cost of producing implants is expected to decrease. This could make advanced medical treatments more accessible to a broader population.
7. **Faster Approval and Certification Processes**: As regulatory bodies become more familiar with AM technologies and their applications in medical implants, the approval and certification process could become faster and more streamlined, facilitating quicker access to new treatments.
8. **Sustainability**: AM offers the potential for more sustainable manufacturing processes due to its efficiency and waste reduction capabilities. This aspect is increasingly important in medical manufacturing, where reducing the environmental impact is a growing concern.

Question 1 Examiners Report.

This question related to the production of orthopaedic implant through additive manufacturing operations.

Part ai) required students to identify a suitable AM process for the part. The vast majority chose LPBF, which was the most sensible choice given the design requirements. Very few answers discussed the biological requirements in relation to the production method or the material choice.

Part aii) asked for a discussion of the post processing steps that are specific to implants. Answers were well developed for general AM applications but less so for medical applications.

Part aiii) asked for a discussion on process choice and cost factors. Most answers cited patient specific attributes through customisation, although this is in fact less well developed in practice.

Section c) required the production of control charts for a set of manufacturing data. Answers to part i) were correct for the vast majority of the responses, although those of part ii) were less comprehensive and let down by mistakes in calculation or using incorrect expressions for finding Cpk. Part iii) delivered a mixed bag of responses, lower scoring answers gave limited recommendations, whilst higher performing students dug deep into the data and showing good insights and offered effective recommendations.

Section b) allowed the students to free-think future developments. Some good answers on the whole although there was little mention of bio-inspired AM technologies, which is perhaps the most obvious next step in this space.

Question 2

(a) A good answer will give a basic introduction to each composite type, be able to give a couple of manufacturing steps, and make a relevant point about the inclusion of resin. A good answer will give a very clear explanation of the composite types, a couple of manufacturing steps, a very clear explanation of the role of resins in each type and make a clear link to the properties of the resin. An outstanding answer will need to cover all areas requested with excellent detail.

It is likely, based on the lectures, that students will refer to Core honeycomb composites. Rolls of a aramid paper are cut to the dimensions required to build up layer by layer to the approximate lateral dimensions of the component. Adhesives are positioned in stripes in each layer and pressure and heat are used to bond. Then the honeycomb is created by expansion. These are dipped into a resin and cured (set) thermally. The paper has good ductility and the resin is providing excellent stiffness while allowing the overall structure to still have an excellent strength to weight ratio for applications such as helicopter blades, winglets, aircraft flooring. At this point they can be cut to dimensions required. This core honeycomb is relatively easy to shape/machine. In all cases these are part of a sandwich structure with a thin shell material on either side. There are many properties that candidates can consider, for example the resin stiffness upon curing, the ease of curing, the rheology to ensure it will coat evenly upon dip-coating, etc.

The second composite likely to be discussed Is carbon fibre composite, often used in cars, high end bicycles, wind turbine blades. It is likely they will focus on prepreg for this answer because of the discussions in lectures. The manufacturing steps may start with polymerization of acrylonitrile and spinning of the fibres before they are carbonised in a furnace. These are woven into fabrics, dipped in a resin, compacted and then coated in protective layers. The resin binds the carbon fibres together, provides the stiffness to the material but also allows for pre-preg allows it to be shaped and layered by the end manufacturer into the component they wish prior to curing. The viscosity is again important as it will have to flow between the fibres but this can be tuned depending on the final production process. Higher viscosities are linked to improved toughness.

(b) (i) This is a short question but a good answer would link the carbon nanotube's structure to high strength and stiffness values, improved durability and potentially improved damping depending on the application. They would note that this can have a reinforcing effect on a polymer matrix in a composite. Essentially, this would be a composite at multiple scales, with carbon fibres, a resin matrix, and nanomaterials within the resin matrix. Some candidates may focus on where there are benefits to improve electrical conductivity as this has also been discussed in lectures.

(b) (ii) In terms of the materials, it is likely that the main challenge that will be discussed is how to ensure it is well dispersed throughout the product and the potential need for additional ingredients to prevent clumping. In addition, comments are anticipated on the challenge of quality control and ensuring that carbon nanotubes of the right length and wall thickness are consistently supplied, or indeed their conductivity if that is important to the application. These are very challenging to test upon receipt but are critical to the final performance within a resin. A basic answer will explain one challenge, a strong answer will be able to clearly describe 2-3 challenges.
In terms of the process, it is anticipated that candidates will consider chemical process design and think about what changes may occur. One aspect that may be raised is the need to re-design the addition of materials, material storage, waste streams and recycling streams. There will need to be an update to the mass and energy balances, and there will likely be a new mixing process included unless the CNTs can be added in an existing step. A strong answer will also describe the need to update the Hazard and Operability study.

(c) (i) In a good definition of high performance materials, candidates should refer to how materials through their intrinsic properties or different ways of processing them can demonstrate a superior performance compared with other materials used for the same application. A strong answer will give a few examples, such as resistance of certain steel components to corrosion due to their processing and alloy type, or stiffness to mass ratio for example.

In terms of biomimetics, a strong answer will convey an understanding that the behaviour of biological systems are studied and through this understanding we can develop physical systems that replicate their behaviour and physical/chemical properties. A more general definition can just consider using ideas from analysis of biology and translating them to technology. A strong answer will give some specific examples.

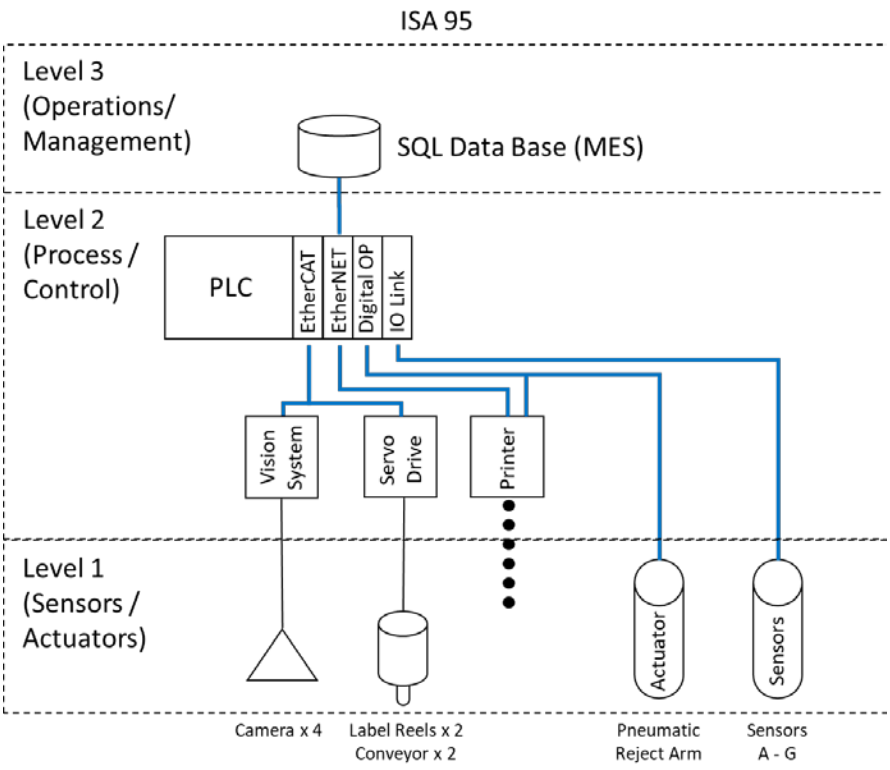
(c) (ii) In this answer, a basic answer will highlight that toughened glass is created by ensuring there are strong compressive forces close to the outside faces of the glass, and more tensile forces within. A good answer will include details about how this is carried out chemically through ion diffusion, specifically using a molten salt bath to diffuse the smaller sodium ions out of the glass and the larger potassium ions into the glass, leading to a higher compressive stress. A very strong answer will give more context and note that the toughness of glass is linked to the presence of flaws and either keeping them as small as possible, or including a stress that will oppose any applied tensile stress, thus reducing the overall stress flaws are exposed to, so the fracture stress is increased.

(c) (iii) There were specific examples described in the lecture and if students rely on this, that is acceptable. However, all thoughts and approaches will be considered as long as they link a biological phenomenon to a high performing glass (with whatever definition of performance they choose). One example is using the composite structure of nacre for inspiration and so there are thin layers of glass with transparency and stiffness required, but then an inter-layer soft organic phase or resin phase that are very tough connecting ligaments. An excellent answer will give a clear description of the natural phenomenon and how it gives outstanding mechanical performance and then how that can be translated to a glass material.
A different high performance could be self-cleaning, in which case examples from lotus leaves could be explained, thinking about the change in surface structure and surface chemistry to drive water repellence and self-cleaning. Again, a strong answer needs to explain how this could be translated to glass through surface modification with lasers and surface coatings.

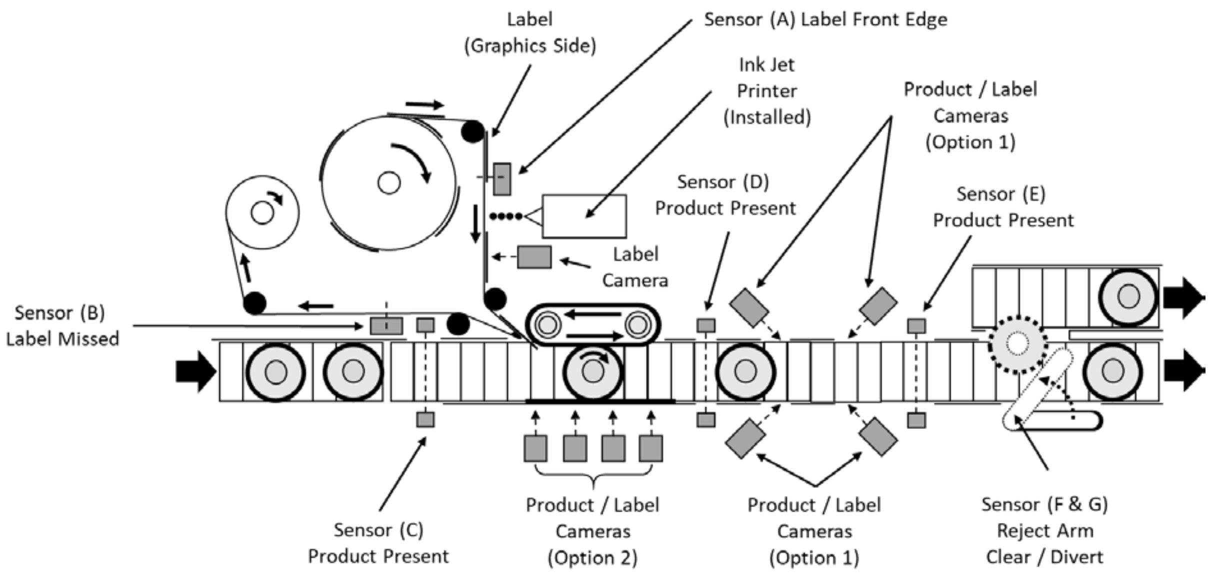
Examiners Report Question 2
Overall, this was answered well, with 30% with marks in the 70-100% range, and almost three quarters of the candidates receiving more than 60%. There was only one candidate with a particularly low score, where they answered very briefly and in a number of cases did not answer a number of questions. Overall, however, the answers indicate that the candidates engaged well with the majority of topics covered in this question. There was an excellent level of understanding shown by a large number of students. The questions about composites were most challenging and showed a wide variety of answers, whereas questions about high performance materials and glass manufacturing were answered strongly by the majority of the candidates

Question 3

ai)



aii)



The system has been updated with a number of new components:

Components	Operation / Connection
Integration to Manufacturing Execution System (MES / Data Base)	Connection to SQL Database for information requests (Product Use by Dates and Production Batch Numbers) Note:- modern PLC's can provide software functions to connect directly into networked database's. The database is connected to the PLC via Ethernet. (Ethernet IP)

Ink Jet Printer	An ink jet printer has been installed, allowing the Product Use by Date and Production Batch Number to be printed onto the paper labels. The ink jet printer is connected to the PLC via Ethernet for Data Communications, and uses digital IO to trigger deterministic print operations.
Product Label Cameras	A vision system has been installed that can support four cameras. The vision system has software tools integrating camera images and performing character recognition. Option 1. The cameras have been installed to allow the different sides of the product to be seen. (Note:- product orientation can vary) Option 2. The cameras have been installed along the length of the label applicator belt. As the product rotates down the belt, different sides of the product will be seen. The vision system is connected to the PLC via EtherCat.
Sensors	Various sensors on the system have been upgraded: Sensor A & B - Optical through beam sensors. Sensor C, D & E - Optical reflective sensors. Sensors F & G - Inductive sensors, mounted to detect cams on the reject arm. All sensors should us IO Link technologies. This technology provides additional information on sensed signal quality and can be used to support maintenance processes such as lens cleaning. The sensors are connected to the PLC via IO Link.

aiii)
Potential causes of operational issues and improved sensor choice.

Sensor ID	Potential Cause of Operational Issue	Appropriate Sensor
A	This sensor needs to detect a difference in the reflected signal between the label and the backing material. The performance of this sensor will be affected by changes in label colours and backing material. Due to the nature of its diffused operation it will also be sensitive to the lens becoming dirty. This sensor provides trigger information, defining the front edge of the label. Therefore, care should be taken in considering which label feature is used as a sensor trigger point. (Transition between label and backing material may be hard to detect and may vary between label reels. Printed features on the label may also vary across different labels depending on print quality.)	Optical Through Beam sensor for label applications. Single unit with different slot sizes depending on label thicknesses. Consider the response time of the sensor in detecting labels, as this will affect the location of where print starts on the label. Consider IO Link technologies. They provide additional information on read quality that can be used

	An Optical Through Beam sensor may provide a more reliable operation in detecting the difference between paper labels and semi translucent backing materials.	to drive maintenance processes, such as lens cleaning. Standardise label materials and ensure processes are in place to inspect the quality of incoming label reels.
B	This sensor has the same requirements as sensor A, although its response time may be less critical.	Use the same sensor as selected for A. (Standardise sensors and match configuration requirements)
C	This is a mechanical contact sensor that will have a limited life and the mechanical components, such as the lever arm, can deform over time or with product jams. This sensor provides trigger information, defining when a product is present to be labelled. The deformation of the lever arm will affect when the trigger occurs and when a label is fed. Non-contact sensors would be more suitable for this application.	Optical reflective sensor with a reflector being positioned on the far side of the conveyor. The operation of the sensor should be setup to operate like a beam break when the product is present. Consider IO Link technologies. They provide additional information on read quality that can be used to drive maintenance processes, such as lens cleaning.
D / E	This sensor needs to detect a difference in the transmitted signal between the labelled and none labelled portion of the product. This would be very challenging considering the labels are paper. A camera solution would be more appropriate. An optical diffused sensor may work but it would be reliant on detecting and analysing the difference between label features and the product. A camera based solution would be more reliable.	Camera based solution. This may need multiple cameras as a) the orientation of the product can vary, b) the size of the label is unknown and the label is being placed on a curved surface. Replace sensors D / E with Optical Reflective sensors as used for sensor C. This replacement sensor could be used to trigger camera/s performing label detection.

b) The label applicator and reject station have several interdependent processes that can cause bottle necks and affect the overall performance of the station. These processes include:

1) Label preparation.
2) Printing of the label and feeding it forward to the label separator.
3) Label application onto the product.

4) Verifying information on the labelled product.
5) Rejecting a product.
6) General conveying of product.

Assumptions: The maximum speed of the label feeder, and label applicator will be limited by either the maximum inkjet print rate or label application rate.

Process	Sub Process Activities	Implications	Tests
Label preparation.	-Acquire MES data to be printed onto the label.	-Does the print data need to be obtained once per batch or once per product?	PLC / Data base integration. -Data request cycle times.
Label printing and positioning at the label separator.	-Max print rate of the inkjet printer when printing Use by Date and Batch Number. -Max constant feed rate of the label print window in front of the printer. (Accounting for ramp up / down profiles required).	-Sensor A provides a trigger signal to start printing. Delay required before printing starts. -The label applicator is buffering two tags before they are applied to the product. Care needs to be taken when changing between production Batch Numbers and / or Use by Dates.	PLC / Reel Servos / Ink Jet Printer. -Label print cycle times. -Identify whether the servo drives, or the printer will be the limiting factor. -Identify upper label reel feed rate. -Identify upper label print rate. Note:- the upper bounds may already be defined by the data base request.
Label application on to the product.	-Max applicator roll speed, providing good quality labelled products.	-Sensor C provides a trigger signal to start label feed. Ensure the label is in contact with the product, feed the remaining label with slack to limit jamming. (Better results may be achieved if the label reel speed is slightly higher than applicator belt speed.)	PLC / Reel Servos / Product / Label Applicator Belt. - Pass products through the labelling processes, to determine the upper speeds of the label applicator belt. Note:- the upper bounds may already be defined by Label printing process
Verification of label information.	-Time required to perform a label verification process. Verify the label is correctly printed / located. -This may also require MES data to	-Sensor D provides a trigger signal to start label verification process.	PLC / Camera Inspection process. -Test cycle times of the label verification process. Test with both good and bad products. Note:- the product is continuously moving and a valid result is

	be acquired for the verification process.		required prior to the product reaching the reject Sensor E.
Product reject and reset.	-Time required to reject a product. Move the reject arm into a reject position for a set time and then return it to the normal position.	- Sensor E provides a trigger signal to start the reject process. Ensure the reject arm is diverted before the product is present at the reject location and resets for continued operation.	PLC / Reject Arm -Test cycle times required to reject a product. Determine how long the reject arm should be in the reject position.

Tests should be phased into following structure.

1) Ensure hardware has relevant interfaces and can interconnect.
2) Ensure the system protocols are available to allow hardware operations.
3) Define unit tests, ensuring individual hardware components and local software functions work correctly. (Label Preparation, Verification of Label Information, Product Reject & Reset)
4) Define system tests that allow integrated tests to be performed across units. (Label printing and positioning at the label separator, Label application onto the product.)
5) Perform dynamic tests as discussed previously to determine limitations of the labeller and reject stations performance.

ci) Low-Cost Applications on the Labeller and Reject Station.

The low-cost applications chosen, focus on monitoring operations rather than critical control applications. These applications include:

Application	Description
Andon Lights	Piggyback sensing / monitoring of the control system to provide status of the system through operator light beacons.
Label Reel Replenishment	Sensing used to monitor the status of the label reel, warning operators that it will soon need replacing.
Power Monitoring	Current sensing of components using high energy levels (Conveyor / Belt motors). This information can be used to determine power usage.
Reject Buffer Full	Monitoring of the reject station, counting / trending the number of rejects to warn operator of potential issues.
Remote Monitoring	Low-cost technologies such as raspberry pi's have software tools to allow information and dash boards to be easily shared over web / mobile services.

cii) Limitation of Low-cost automation hardware:

Limitation	Description
Hardware Robustness	Low-cost computing and software tools are not designed to fail in safe operating mode. Hardware has not been designed for operation in harsh environments. Hardware has not been tested to the same degree as automation control hardware.

Hardware Continuity	Low-cost computing and software tools (consumer based) may not have production lifetimes and replacement guarantees as in automation control hardware.
Support	Low-cost computing and software tools are often developed / provided through open-source communities. (Service and support will not be through the traditional service phone lines)

Examiners report Question 3
Q3 was based on material from the MSE module, a) PLC Lectures, b) Sensors for Automation, c) Low Cost Automation and d) Robot Lab Practical. The question was only attempted by 5 Candidates.

ai) Answers showed little reference to Architecture models, the layers could have been made more distinct, most of the diagrams listed hardware components and showed little reference to data systems such as MES. Most Answers made a general reference to ethernet but not to industrial networks. (EhernetIP, EtherCAT, DeviceNet.....).

aii) Three of the answers discussed the use of printing and that text verification was required. (1275I & 1281H) discussed RFID solutions that are none readable! One answer clarified that the printing option had to be installed and integrated into the solution.

aiii) Only one candidate actually listed out the sensor discussed in the question (A, B,C, DE) discussing specific issues and replacement sensor types that should be used. Other answers discussed the topic area showing general knowledge of the sensors and the issues in using them but did not specifically answering the question. (e.g. Table showing generic pros and cons of different sensors).

b) Only one candidate recognised that bottle neck processes need to be identified, also providing specifics around Unit and System tests that need to be carried out. Other answer provided a general discussion around testing but not the specific steps that would be carried out.

c) This section of the question was answered well. Candidates raised the same core common issues. Some candidates discussed a wider range of issues and provided better discussion on the topic.

The question covered a good mix of the material covered in the MSE module and the robot lab activity.

Question 4
(a) Students must provide a brief description of a logistics system including the three key components with the following points of comparison highlighted based on the components of a logistics system:
  - <u>Storage and retrieval:</u> Inventory for bank is critical and sensitive to external access. It must be protected and closely accounted for. The bank must plan for human resources/ server availabilities, whereas the automobile manufacturer must account for spare parts availabilities including the inventories on both production and consumer side of logistics to keep the production running.

- Transport: The transport in bank involves movement of uniform products which might include cash or gold, that do not change in shape or form. The bank must also manage the ATMs across the city and ensure sufficient cash for customer satisfaction. On the other hand, the automobile manufacturer manages transport network comprising of multiple potential stakeholders, redundant suppliers, and raw materials that change shape/ form across through the process. This is because automobiles are often manufactured with raw materials sourced from diverse locations.
- Order Management: For the case of the bank, this is about ensuring their servers and staff can handle the increased crowd in their branches. Whereas the automobile manufacturer must ensure the products are available well in time to cater the market demand.

[Standard answers will provide a generic discussion on the differences, whereas excellent answers will highlight the differences using examples from banks and automobile (or other) industries.]

(b) This is the classic travelling salesperson problem, which needs to be solved for the given adjacency matrix. Since the given matrix comprises of the common multiplier (x10), evaluating for the below matrix shall result in the required shortest path:

	D	**1**	**2**	**3**	**4**
D	-	20	30	10	11
1	15	-	14	10	11
2	30	22	-	20	14
3	19	16	19	-	13
4	16	14	17	16	-

Steps followed while evaluating for the shortest path are as follows:

Identify the minimum values in each row of the matrix:

	D	**1**	**2**	**3**	**4**	**Row Minimums**
D	-	20	30	10	11	10
1	15	-	14	10	11	10
2	30	22	-	20	14	14
3	19	16	19	-	13	13
4	16	14	17	16	-	14
Total row minimum						61

Now, reduce the values in each row of the matrix by the row minimum:

	D	**1**	**2**	**3**	**4**	**Total Column Minimums**
D	-	10	20	0	1	
1	5	-	4	0	1	
2	16	8	-	6	0	
3	6	3	6	-	0	
4	2	0	3	2	-	
Column minimum	2	0	3	0	0	5

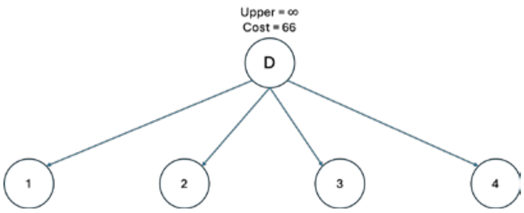
Reduce the values in each column of the matrix by the column minimum:

	D	**1**	**2**	**3**	**4**
D	-	10	17	0	1
1	3	-	1	0	1

2	14	8	-	6	0
3	4	3	3	-	0
4	0	0	0	2	-

The total minimum 'cost' is therefore 61+5 = 66. This will be the cost of node 'D' in the state-space tree, which also represents the lower bound. The upper bound is initially considered to be ∞.

Drawing the state-space tree:



Solving for node 1, the updated reduced matrix is as follows:

	D	**1**	**2**	**3**	**4**
D	∞	∞	∞	∞	∞
1	∞	∞	1	0	1
2	14	∞	-	6	0
3	4	∞	3	-	0
4	0	∞	0	2	-

Since each row and column has a zero value, we can say that this matrix is a reduced matrix. The cost of adding the segment D→1 is d(D, 1) + r + r'(1) = 10 + 66 + 0 = 76.

Solving for node 2:

	D	**1**	**2**	**3**	**4**
D	∞	∞	∞	∞	∞
1	3	-	∞	0	1
2	∞	8	∞	6	0
3	4	3	∞	-	0
4	0	0	∞	2	-

This is also a reduced matrix. The cost of adding the segment D→2 is:
d(D, 2) + r + r'(2) = 17 + 66 + 0 = 83.

Solving for node 3:

	D	**1**	**2**	**3**	**4**
D	-	∞	∞	∞	∞
1	3	-	1	∞	1
2	14	8	-	∞	0
3	∞	3	3	∞	0
4	0	0	0	∞	-

This is not a reduced matrix since row '1' does not have a zero. Therefore reducing the matrix will give:

	D	**1**	**2**	**3**	**4**
D	-	∞	∞	∞	∞

1	2	-	0	∞	0
2	14	8	-	∞	0
3	∞	3	3	∞	0
4	0	0	0	∞	-

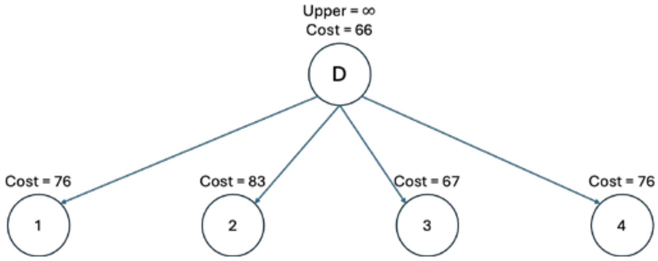
The cost of adding the segment D→3 is: d(D, 3) + r + r'(3)= 0 + 66 + 1 = 67.

Solving for node 4:

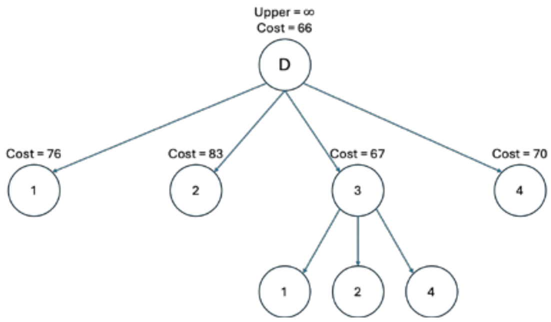
	D	**1**	**2**	**3**	**4**
D	-	∞	∞	∞	∞
1	3	-	1	0	∞
2	14	8	-	6	∞
3	4	3	2	-	∞
4	∞	0	0	2	-

The cost of adding the segment D→4 is: d(D, 4) + r + r'(4) = 1 + 66 + 9 = 76

The state space tree is therefore given by:



Choosing the lowest cost branch, 3, we add the segment D→3 to the route.



Now, solving for node 1:

	D	**1**	**2**	**3**	**4**
D	-	∞	∞	∞	∞
1	∞	-	0	∞	0
2	14	∞	-	∞	0
3	∞	∞	∞	∞	∞
4	0	∞	0	∞	-

This is a reduced matrix. The cost of adding 3→1 is 3+67+0 = 70.

Solving for node 2:

	D	**1**	**2**	**3**	**4**
D	-	∞	∞	∞	∞
1	2	-	∞	∞	0

2	∞	8	-	∞	0
3	∞	∞	∞	∞	∞
4	0	0	∞	∞	-

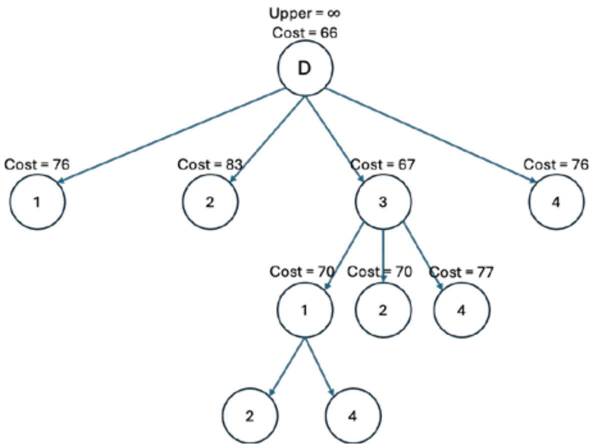
The cost of adding 3→2 is 3+67+0 = 70.

Solving for 4:

	D	**1**	**2**	**3**	**4**
D	-	∞	∞	∞	∞
1	2	-	16	∞	∞
2	14	8	-	∞	∞
3	∞	∞	∞	∞	∞
4	∞	0	0	∞	-

This is not a reduced matrix. The cost of adding 3→4 is 0+67+10 = 77.

Choosing the lowest cost branch, we add D→3→1 to the route (we could have also chosen 2, which has the same cost):



Now, solving for node 2:

	D	**1**	**2**	**3**	**4**
D	-	∞	∞	∞	∞
1	∞	-	∞	∞	∞
2	∞	∞	-	∞	0
3	∞	∞	∞	∞	∞
4	0	∞	∞	∞	-

The cost of adding 1→2 is 0+70+0 = 70.

Solving for node 4:

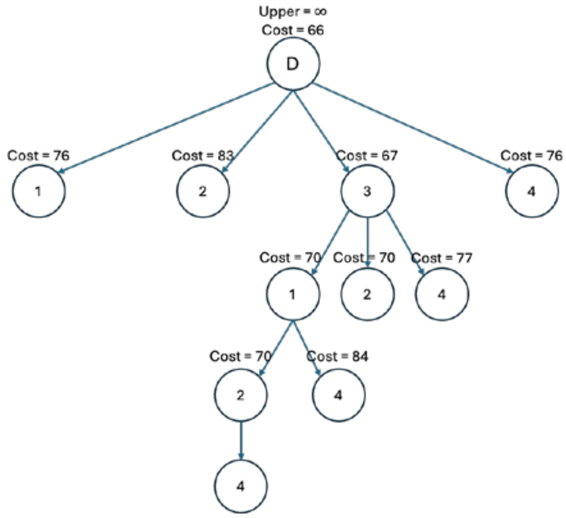
	D	**1**	**2**	**3**	**4**
D	-	∞	∞	∞	∞
1	∞	-	∞	∞	∞
2	14	∞	-	∞	0

3	∞	∞	∞	∞	∞
4	∞	∞	0	∞	-

This is not a reduced matrix. The cost of adding 1→4 is 0+70+14 = 84.

The lowest cost is 1→2. Hence we add it to the route, i.e., D→3→1→2.

The state space tree is therefore:



Finally, the cost for 2→4 is given by:

	D	1	2	3	4
D	-	∞	∞	∞	∞
1	∞	-	∞	∞	∞
2	∞	∞	-	∞	∞
3	∞	∞	∞	∞	∞
4	0	∞	∞	∞	-

The cost of adding 2→4 is 0+70+0 = 70.

It can be observed that the cost 70 is associated with the route D→3→1→2→4→D, which is lower than the least cost associated with any other nodes. Any other path taken will have a cost greater than 70, and therefore we can terminate our calculations here. Therefore, the optimal route is D→3→1→2→4→D with a total travelled distance of 700 meters.

NOTE: The students must mention the lower and upper bounds along the tree leaves, this is important information which cannot be ignored.

(c) Since the matrix has a common multiplier, i.e. x100, solving for the below matrix shall result in the required solution:

	D	1	2	3	4	5	6
D	-	20	18	14	16	12	19
1	20	-	22	18	30	26	28
2	18	22	-	32	20	22	21
3	14	18	32	-	20	22	21
4	16	30	20	20	-	30	22

5	12	26	22	22	30	-	36
6	19	28	21	21	22	36	-

(i) Clarke Wright algorithm can be used to evaluate the number of buses required to minimise the overall distance travelled.

In the first step, the savings in distance across all possible pairs of stops are calculated. The savings compare the bus going to the next stop directly, versus coming to the depot and then going to the next stop. Distance savings for stops i and j are calculated as:

$$S_{ij} = d_{D,i} + d_{D,j} - d_{i,j}$$

Since there are six stops and the adjacency matrix is symmetric, the total possible pairs of stops are:

$$= C_2^6 = \frac{(6)!}{(2)!(6-2)!} = 15$$

The 15 pairs of stops with the corresponding savings in descending order are shown below:

Pairs	Savings	Pairs	Savings	Pairs	Savings
(1,2)	16	(3,6)	12	(1,5)	6
(1,3)	16	(1,6)	11	(3,5)	4
(2,6)	16	(3,4)	10	(2,3)	0
(2,4)	14	(2,5)	8	(4,5)	-2
(4,6)	13	(1,4)	6	(5,6)	-5

Assigning the top pair to the first bus, we move down the list of stops adding the corresponding passengers if they all fit within the capacity of the bus. When the passengers for a given pair exceed the capacity, and do not overlap with already assigned stops, they are assigned to the next bus. These steps are followed until all the stops are accounted for. The order pairs allocated to the buses, with total distance savings being 45 after following the above procedure, are listed below:

Bus	Pairs	Capacity	Savings
Bus 1	(1,2), (1,3)	13	32
Bus 2	(4,6)	11	13
Bus 3	5	3	0

It should be noted that the stop 5 is assigned to the 3rd bus because both pairs (4,5) and (6,5) are associated with negative distance savings, and therefore make it more efficient for the bus to go to stop 5 from the depot.

The route for each bus is, for bus 1: D-2-1-3-D for bus 2: D-4-6-D and for bus 3: D-5-D. The total distance saved, compared to the buses going individually to each stop and back to the depot is 4500 units.

However, the Clarke Wright heuristic uses a greedy approach and therefore the Holmes Parker extension must be used to check any further possible optimisation.

To check for this, we branch off first at the stop pair (1,3) instead of (1,2) and follow the same procedure. The order pairs allocated to the buses if we ignore the first pair, with total savings 50, are shown below:

Bus	Pairs	Capacity	Savings
Bus 1	(1,3), (3,6)	13	28
Bus 2	(2,4), (2,5)	14	22

The updated solution, after the observing a greater saving in step 4 above, is therefore the following: route for bus 1: D-1-3-6-D, and route for bus 2: D-4-2-5-D. Total 5000 distance units are saved following this route, compared to the bus going individually to each stop and back.

NOTE: Holmes Parker extension can be continued further, for example by branching at (2,6) instead of (1,2) again. But the students are expected to show only once branching.

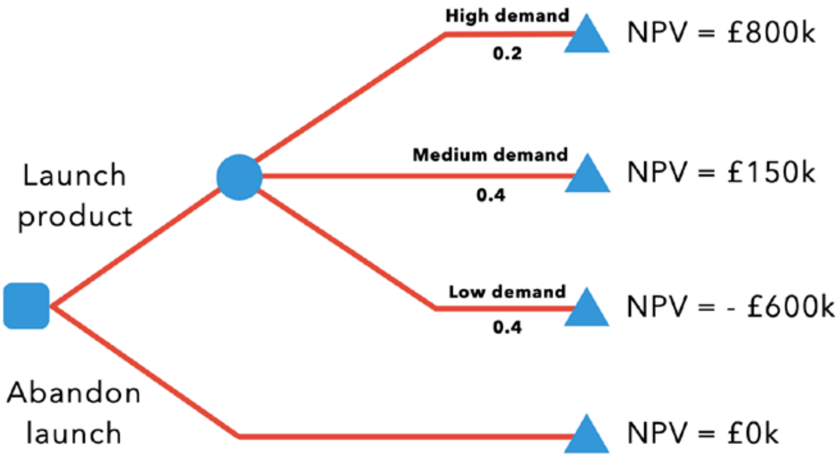
(ii) The total passengers are 27, which is less than the capacity of two buses. A sensible answer to this problem would be to follow the Clarke Wright heuristic assigning the pairs in decreasing orders of distance saving to the bus, but until their full capacities are reached and update the corresponding remaining passengers at the stops. The students must use their knowledge from extra readings and understanding of the Clarke Wright heuristic to address the problem. It is not expected for the students to reach the correct answer but an attempt to answer the question demonstrates that they have understood the concept.

Examiners Report Question 4

This question was based on the issues of logistics discussed in the AOM module. It was a popular question, answered by 20 candidates. Part (a) required candidates to compare logistics operations in manufacturing and service-based companies. The question was answered reasonably well, with many students structuring their responses around issues on storage and retrieval, transport, and order management. Weaker responses simply/wrongly suggested that service-based companies do not have any material logistics involved, and only deal with information transfer. Good responses discussed issues relating to resource management in service companies as the key issue. Part (b) required candidates to use the branch and bound algorithm to determine the shortest route to transport passengers in a network. Some candidates did this correctly, some made simple arithmetic errors, and many candidates used the initial distance matrix instead of the reduced matrices to identify lowest cost nodes. A few candidates did not use branch and bound algorithm and used trial and error to solve the problem. Part (c) required candidates to use the Clarke-Wright algorithm to identify the minimum number of buses required. This was done correctly by many candidates. The extension to this part was answered with varying quality.

Question 5

(a) Students are expected to draw a decision tree to assess whether or not the product should be launched with the available information. [10 Marks]



Based on the decision tree, the expected value of launching the product can be calculated as:
EV= £160,000 + £60,000 - £240,000 = - £20,000

[8 Marks]

The calculation suggests that it would be wise to abandon the launch of the amplifier which has a higher expected value (£0 > - £20,000) than launching the product.

[2 marks]

(b) The expected value of market research is given by the difference between the expected profit the company can make if the decision is made without market research, which is £0.

[10 marks]

The expected profit the company can make if the decision is made with market research, given by 0.2 × £800,000 + 0.4 × £150,000 + 0.4 × £0 = £220,000

[15 marks]

Hence, the maximum fee that must be paid to market research is £220,000.

[5 marks]

(c) In order to determine whether to pay Resi to undertake research, the value of the research must be evaluated. The expected value of the project given research results will be the sum of NPVs of the decision given the research outcome, multiplied by the probability of each research outcome.

If further market-research us undertaken, the revised (posterior) probabilities upon receiving the market research results can be found using Bayes Rule. The probabilities of each research outcome are given as follows:

Positive outcome:

$P(P) = P(P \mid H) \times P(H) + P(P \mid M) \times P(M) + P(P \mid L) \times P(L)$

$P(P) = 0.8 \times 0.2 + 0.5 \times 0.4 + 0.1 \times 0.4 = 0.4$

Similarly, Negative outcome:

$P(N) = P(N \mid H) \times P(H) + P(N \mid M) \times P(M) + P(N \mid L) \times P(L)$

$P(N) = 0.2 \times 0.2 + 0.5 \times 0.4 + 0.9 \times 0.4 = 0.6$

[15 marks]

Next we consider the likelihood of each deman being predicted given the research. Conditional probabilities of the actual demand given whether it is a positive or negative recommendation are:

e.g. Demand is high, research is positive:

$P(H \mid P) = [P(P \mid H) \times P(H)] / P(P) = 0.8 \times 0.2 / 0.4 = 0.4$

e.g. Demand is medium, research is positive:

$P(M \mid P) = [P(P \mid M) \times P(M)] / P(P) = 0.5 \times 0.4 / 0.4 = 0.5$

e.g. Demand is low, research is positive:

$P(L \mid P) = [P(P \mid L) \times P(L)] / P(P) = 0.1 \times 0.4 / 0.4 = 0.1$
e.g. Demand is high, research is negative:
$P(H \mid N) = [P(N \mid H) \times P(H)] / P(N) = 0.2 \times 0.2 / 0.6 = 0.067$
e.g. Demand is medium, research is negative:
$P(M \mid N) = [P(N \mid M) \times P(M)] / P(N) = 0.5 \times 0.4 / 0.6 = 0.33$
e.g. Demand is low, research is negative:
$P(L \mid N) = [P(N \mid L) \times P(L)] / P(N) = 0.9 \times 0.4 / 0.6 = 0.6$

[15 marks]

We can now find the expected value from each potential decision: to launch or not to launch the product. E.g. if the recommendation by market research is to launch, the expected profit can be calculated as:
EV(Launch | P)=P(H|P) × £800k + P(M|P) × £150k + P(L|P) × −£600k
= 0.4 × £800k + 0.5 × £150k + 0.1 × −£600k = £335k
EV(Not Launch | P)= £0k
If the recommendation by market research is not to launch, the expected profit can be calculated as:
EV(Launch | N) = P(H|N) × £800k+P(M|N)×£150k+P(L|N)×−£600k
= 0.067 ×£800k+0.33 x 150k+0.6×−£600k = −£257k
EV(Not Launch | N)= £0k

[15 marks]

Finally considering the probability of the research being positive or negative, as in table 1, we find:
EV(Decision given research)= 0.4x335+0.6x0=£134000
From (b), we know that:
EV(without market research) = £0k
The value of the Bio-Marketing information is the difference between the expected values with and without it: £134 000 – £0 = £134 000.
This is greater than the cost of the information, £50 000. Therefore Cymba-Tech should decide to use the services of Resi.

[5 marks]

Examiners Report Question 5

This question asked the students to develop a decision tree model to decide whether a new product should be launched based on the expected values of cash flow with or without perfect information, and how much should the company pay for further market research to obtain information. This was a very popular question. Most students developed a reasonably good model of the problem using the Bayesian approach, with a number of students obtaining full marks. Students who obtained lower marks included those who did not carry out a conditional probability approach; and those who did not explain their results. There were a number of incomplete attempts. Most of the students did not present the decision tree in part a. In part b many students did not fully answer all parts of the question or did not apply the conditional probability calculation correctly. Part c was overall the best answered, although there were a few attempts where there was no use of the Bayes rule.

Question 6

a) A system boundary is used to define what factors should be included for a particular environmental analysis. It should separate those parts of the process which are being examined from those which are not part of the process being examined.

For the batteries, the following factors should be considered: mining of either lithium or sodium and other critical metals, electrode material production, battery manufacturing process, transport of components between production stages, the weight and volume of the battery, how it affects the density with which the product can be packed for transport, and end-of-life disposal.

The analysis is of just the battery, so the production of the item that the battery is used to power is outside the boundary. However, the efficiency and lifetime of the battery may have implications for the lifetime of the product, particularly if the battery is fully integrated into the product (such as with some phones).

The analysis should be used to identify the overall difference in environmental impact, as well as the phases with the greatest difference. It should also be used to identify the specific sub-processes which most significantly contribute to the overall environmental impact.
Additional factors: Not specifically mentioned are the factors associated with using batteries in general as an alternative to other methods of energy storage.

b) Technical: Li-ion batteries are complex structures and contain many different components and materials. Li-ion batteries come in many different packages and conformations, meaning they are not fully standardized, making the physical unpacking process more difficult. Lithium is mixed in with other metals in the electrodes, such as nickel, manganese, and copper, requiring potentially complex separations steps to selectively extract the lithium. The separations process can also be resource intensive in itself, using both energy and chemical additives. Further, there are potential fire hazards if the processing is not done safely or in a correct environment.

Operational: Recycling of li-ion batteries is currently expensive relative to mining new materials. This disincentivizes new li-ion recycling plants. Further, the logistics of the extraction, collection, transport, and storage of batteries in order to recycle them must be sorted.

Lithium can be resource-intensive and environmentally damaging to extract and process, and current production is not keeping pace with demand. If lithium can be economically recovered through recycling and substituted for virgin material, this would reduce the pressure on the existing supply chain. If the recycling process were more energy and resource efficient than the mining process, this would also reduce the environmental footprint. However, even if all li-ion batteries were recycled and the lithium fully recovered, this would be insufficient to meet future demands for batteries.

c) An alternative application for these batteries would be to be reused at their normal end of life. These are called ‘second life’ batteries. They still hold a charge, but not the full capacity from when they were new. These batteries can be reused for stationary power storage, where having a lower energy density is less of a concern. Second life batteries will help to reduce the demand for new batteries and reduce the environmental footprint of batteries which have reached their traditional end-of-life. However, even these will still need to be replaced and disposed of in some capacity.

Performance is continuing to improve with more research, meaning smaller batteries and less material is necessary for the same performance. Further, there is active research on reconditioning treatments and methods for regaining the charging capacity of batteries which have lost some performance. Similarly, efforts to recondition battery electrodes will reduce the demand for new batteries by extending the life of existing batteries, but these too will need to be disposed of when their useful life ends.

d) Current research is helping to reduce the amount of ‘other’ critical metals in batteries and their electrodes through improved design, improved material distribution, and the use of alternate electrolytes or electrodes. Improved design and material distribution is continually being implemented in practice, improving batteries today. Work on alternative battery components is several years from implementation. These changes will improve recyclability and reduce the need for mining these materials, which in turn will reduce the environmental load from manufacturing.

The primary alternative chemistry of interest right now is a sodium ion battery, which uses sodium instead of lithium. Sodium is a significantly more common element, so there is less of a need for recovery of it, and lower risk of environmental damage from mining for it. It is a highly active area of research but is not yet at the large scale commercial stage. Further, it has a lower energy density and performance, which reduces the business case.

Sodium ion batteries will reduce the environmental damage from lithium mining, but since these batteries have a lower energy density, more of them may be needed, meaning that there may need to be increased mining for the other metals which go into batteries, making the overall environmental impact less simple.

Answer standards:

<u>Basic answers</u>: Demonstrate understanding of the underlying technology of recycling and its environmental justification. May demonstrate lack of knowledge and understanding of some important factors. Examples may be inappropriate. The discussion may be superficial and inaccurate.
<u>Strong answers</u>: Good depth of knowledge and understanding. Will cover the key environmental aspects and provide adequate discussion with pertinent examples discussed with accuracy.
<u>Best answers</u>: Detailed descriptions and analysis. Demonstrate understanding of the more subtle tensions in the environmental assessments. Examples will draw on experience from many different parts of the course together with the student’s own observations. The discussion will be critical and insightful.

Examiners Report Question 6
Question 6 was fairly popular, with slightly more people than average choosing the question. It was generally answered well – most students demonstrated a decent understanding of the material, providing reasonably comprehensive answers to the question parts. The high average (65.92%) and lower standard deviation (8.55%) further indicates that most students had a good understanding of the underlying material. There were several excellent answers, as

demonstrated by the maximum of 78%, while most lower answers (lowest 49%) were due to students running out of time and not answering all parts of the question.