Question 1:

a). Answers could come from some of the following, although candidates could choose a set from their own knowledge and experience. *Good answers will describe the sectors and benefits as described below, excellent answers will extend the range of benefits through their own knowledge of the sectors and technologies*

Sector	Application	Benefits
Semiconductor	Lithography	Increased resolution
	Marking	Increased throughput
	Welding	Melting efficiency
	Cleaning	Increased effectiveness
Aerospace	Welding	Increased resolution
	Additive Manufacturing	Lower costs
	Turbine blade drilling	Lower aero fuel costs
	Laser cladding	Increased Material efficiencies & performance
Automotive	Blank welding	Weight reduction and performance increase
	Laser hardening of gears	Increased performance
Packaging	Laser cutting of die-boards	Increased flexibility & lower cost
	Laser marking	Increased flexibility, lower speeds & costs
Medical	Additive manufacturing of implants	Increased capabilities and lower costs

Devices		
	Laser cutting of stents	Increased device resolution and performance.

b) (i) Operating principles A schematic of a fiber laser is shown below:

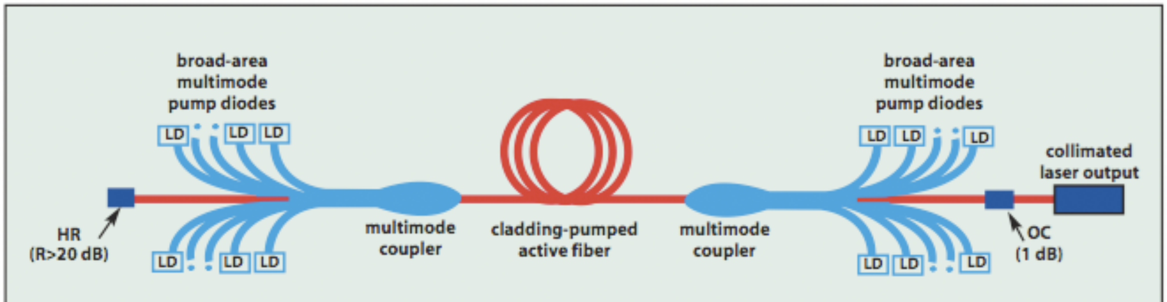


Figure 1. *Schematic of a typical single-mode fiber laser utilizing single-emitter diodes.*

1) An optical fiber is used as the active medium for the laser that has been doped in rare- earth elements, most often Erbium.

2) Fibre pigtails are spliced to the main fiber, which are then connected to many low power laser diodes (LD). These act as pump sources that energise the main fibre and activate the energy levels of the rare-earth dopant.

3) The pump laser is focused into cladding that sits around the fiber core. By pumping the laser into the cladding around the core, the pump laser is bounced around inside, and every time that it passes the core, more and more of the pump light is absorbed by the core.

4) High reflectivity and output couplings of the main fiber is achieved by using fibre Bragg gratings, machined into to the fiber that essentially behave as full and partial mirrors for the main fiber cavity.

5) As the LDs energise the main fiber, the rare earth atoms emit the main laser light, which bounces up and down the fiber, amplifying in each pass through interaction with the activated rare-earth atoms.

6) Laser light is emitted by the output coupler and sent into the main delivery unit.

Examiners note: standard answers will cite the main components of the system and give a basic schematic of the system. Good answers will describe the system in more detail. Excellent answers will provide a more detailed sketch that includes the design of the of pump-diode light combiner, mode structure of the laser and the step-index fibre configuration.

(ii) The principal benefits of a fiber laser are: **Compact size**: a fraction of the size of other industrial lasers **High efficiency**: 60% wall-plug efficiencies compared to around 10% of other types of laser **Ruggedness**: can work in harsh environments **Low maintenance costs**: almost maintenance free apart from cooling circuits **Superior performance**: very high beam quality **Lifetime**: Industrial Fiber lasers can last up to 100,000 hrs **Can be applied in any process**:

Examiners note: standard answers will cite the 4 of the main benefits of the system, good answers will cite 6 and excellent answers will cite all of the main benefits.

c) (i) General deliberations:

1. The material is titanium, and is therefore readily processable with high power lasers

2. It is a simple shape with no real complexity

3. It requires a number of through holes of diameter of 1.5mm and depth 5 mm. This gives an aspect ratio of (d/w) 3.33, well within the limits of percussion laser drilling.

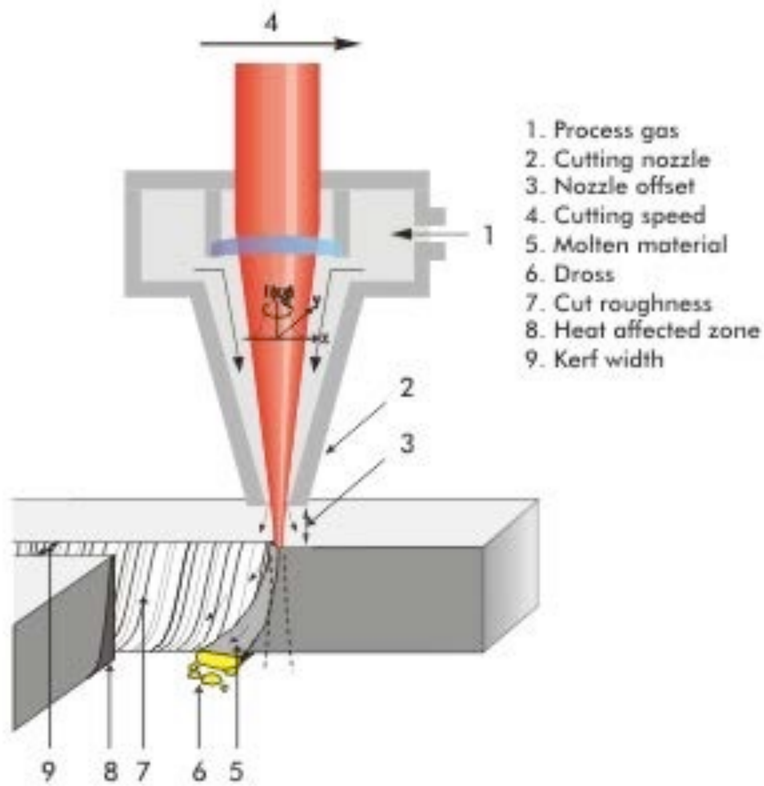
4. The batch size is 500. This is low volume and most suitable for flexible laser-based processing.

5. The tolerances of each dimension are +/- 10%, so that’s 1mm on disk diameter, 0.5 mm on thickness, and 0.15 mm on hole diameter. These are well within the tolerance limits of laser processing

Processing Options:

1. The simplest method is to use Laser cutting to cut out the external diameter, and the 5 through holes

• The process operates as shown in the schematic



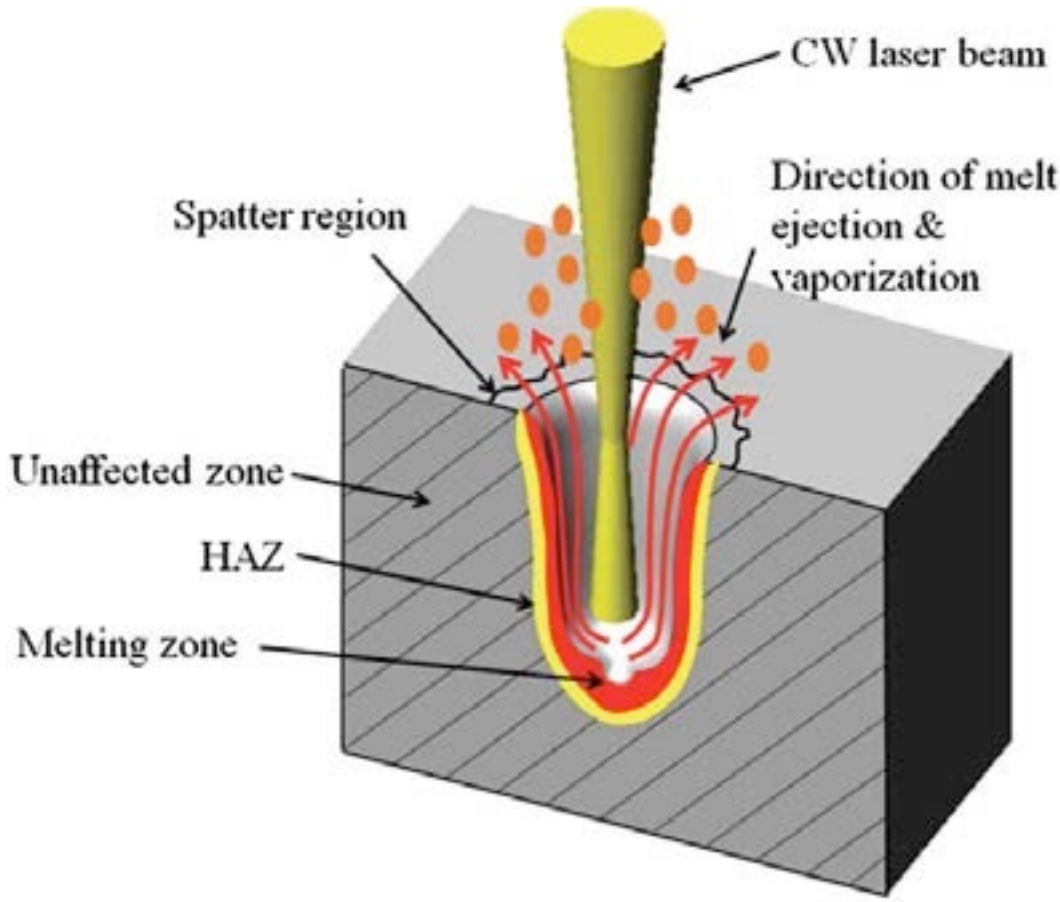
A laser penetrates the material with a coaxial gas jet blowing away the molten material. Traversing the beam through the aid of scanners, or a Cartesian robot, in order to translate the cut with the required path.

• This is a good choice since 5 mm thick titanium plates are readily available, the beam diameters employed can be as low as 40 µm, making the through holes (circles) relatively easy to cut through trepanning the beam. 5mm thick cuts can be achieved easily, even on hard materials like Ti. There will be little waste, and the process will be very high speed, m/s.

2. Another option would be Laser cutting of the outer disk as above, followed by percussion drilling of the holes. Percussion laser drilling is described in the schematic below.

A laser dwells on the material and forms melt pool, the depth of which increases through the material until the hole is made. The laser can be pulsed which would increase the hole quality

• This method is possible, although the aspect ratio of the hole is <10, the quality of the edge maybe a little lower than cutting as above.



3. Option 3 would be additive manufacturing through the power bed process. This is NOT a good choice since AM does not lend itself to the simple part geometry. It would be too slow, and very expensive. Students that offer this solution should be penalised.

Examiners note: standard answers will discuss the main elements of the part and assess its suitability for laser processing. Whilst it is possible to use laser cutting for all features (standard answer), better answers will go on to explore the feature resolution and discuss the reasons why laser cutting/trepanning would be a suitable choice (i.e suitable aspect ratio). Weaker candidates may choose AM, although this is not a good choice as the cost/part would be very high, the part density will be below 100%, and powders are much more expensive than plate.

(ii) An alternative approach would be mechanical machining. Before lasers were invented this method that would have been employed. In comparison we can state the following.

	Productivity	Cost	Precision
Mechanical	Low: very slow processing for the disk, medium for the holes	High due to material, and tooling costs and long manufacturing times. Ti is difficult to machine,	High due to precision being of the order of 10s of μm.
Laser	High speed for both disk and holes	Low due to no tooling costs and high speeds	Medium due to the laser delivering precision around 150 μm.

Examiners note: Standard answers will cite Mechanical: LHH, Laser: HLM, better answers will provide justifications as above.

Question 2:

This question integrates lectures on adhesives, chemical process engineering and polymer analysis. The final part may also draw upon the lecture on biopolymers or any relevant trends that have been identified by the candidate.

(a) A basic answer will correctly identify batch processing as the recommended approach and will briefly note one reason. A strong answer will note two reasons. An excellent answer will either note 3 reasons or add additional clarity and information or examples to the 2 reasons provided.

It is likely that the reasons will be:

- Continuous manufacturing is very challenging to start and stop, whereas batch processing is in discrete volumes and so does not have this issue. If certain volumes are required before stopping production, this is also easier with batch processing as a vessel can work at a wide range of volumes. The product will have an intermittent demand, and so this is also key. If it was a steady, predictable demand then continuous manufacturing may need to be considered.
- Batch processing can handle a range of different product formulations. Each batch has a recipe, certain components can be added and mixed at the required ratio. Then the system can be washed out and re-started for the next product. Also, each step may require a different temperature, mixing time, etc. compared with other formulations. This is not feasible with continuous manufacturing.
- Batch processing is more straightforward when introducing new product innovations.
- There are plenty of additional points and all valid comments were equally accepted.

(b) I would anticipate that a good answer would highlight that a HazOp study is recommended to design out hazards from a system. A strong answer to this part would highlight that this normally happens after the basic steps of a process have been flowsheeted and the temperatures and mass flows are all understood, with unit operations and reactors designed to a basic level. The HazOp studies are run at the process flow sheeting stage to try and identify all the potential hazards if the defined process deviates from the intended design. This is a critical step as it precedes major capital investment, which again is an important point to why it is recommended.

Each answer was considered carefully, as there was scope for approaching this in a number of ways. For example, it was acceptable for answers to refer to the overall structure of the more general process hazard analysis structure, and use this when describing how HazOp is normally carried out. In the more commonly used approach to answer this question, there are 5 key points that were conveyed clearly for a full answer. These to not have to be structured or remembered as presented in the slides, but the main concepts are important to convey somewhere within the answer. A basic answer will list the steps, whereas a strong answer will explain each step and its role in the process. The HazOp study starts by breaking down the process into individual components. Each one is examined separately and the purpose of each component (or intention of the component) is described fully. For example the monomer is supplied in the organic solvent at a specific flowrate and temperature to meet the demand of the reactor.

Possible deviations from this set intention are listed. There are guide words that must be used in turn to explore the deviations. Examples of guide words are expected to help with this explanation. For examine, MORE could examine what happens if more monomer and organic solvent are sent to the reaction that was requested. AS WELL AS may link to a contamination that has ingressed into the flow.

For each of these possible deviations, the team carrying out the HazOp would then examine the possible causes of this deviation. Then, the potential consequences are explored. This will not only be the final consequence, but the chain of consequences.

Finally, the hazard associated with each consequence will be noted to understand the seriousness of the deviation.

The output of the HazOp will enable improved design at the flowsheeting stage.

(c)

Basic answers would recall the key tests discussed during the lectures and detailed in the notes.

Strong answers would draw upon broader messages from the discussions about use, the role of viscosity in delivering appropriate flows for the application, the appropriate pot life for the assembly operation planned.

Excellent answers will include both of the approaches above to some extent and show a clear understanding of the concepts noted.

It is likely that the answers will include:

The viscosity may be tested using a rheometer, to understand how easy/difficult the epoxy will be to apply. This may also be expanded to note that the thixotropy is tested to see how it behaves under stress. There is an industrial 'drip' test carried out and this may be noted instead of rheology to indicate ease of application, but not thixotropy.

The lap shear strength may be tested to understand the adhesive strength and the ultimate load before failure. It may be noted as lap shear strength or to cohesive and adhesive strengths. These refer to the internal strength of the epoxy and to the epoxy-surface bond respectively. A description or a diagram of overlapping pieces bonded together and being pulled apart vertically is sufficient to show an understanding of the test.

The peel strength is measured to understand how the bond will before in certain modes, such as vibration and stretching. The description or diagram should show an understanding that this involves peeling of one layer with vertical loading of the other layer during the test.

Tensile properties can describe the extent to which the epoxy will elongate before breaking and is tested using standard T-bone structures and measuring the force during a constant displacement.

Pot life or the gelling time describes the amount of time from the activation of the epoxy to when it can no longer be used because it is too viscous through gelling. There is a simple test through stirring used in industry but there is also a more repeatable characterisation technique, measurement with a rheometer, that could also be described.

(d) It is not specified in the question what aspect of the performance has changed. However, assuming all of the same testing protocols were used, it would be good to analyse the chemical nature of the epoxy and see if there is a clear cause.

While one point may be to repeat the same set of experiments described in part c, it will be important to highlight that this is to allow comparison with the original performance. After these have been examined, there are additional more fundamental analysis techniques that would be good to use, to better understand what may have happened.

TGA may be described in the answer, which could indicate if there is some unexpected contamination in the formulation. A full answer would give some indication about how this works.

DSC could be used to understand the level of cure achieved and if the glass transition temperature of materials have changed. It was not detailed in lectures, but some answers noted that the level of cross-link would change the readout of DSC, and this was also accepted although no details were expected.

There are a range of other tests that may be referenced, such as taking samples earlier in the process, before curing and dissolving to allow for analysis in GPC. It is possible the polymerisation process changed and different molecular weights were achieved.

A basic answer would include a list of the appropriate tools or approaches, a good answer would show a good understanding of 3 techniques, and a strong answer would identify tools, show a good understanding of what information they could be used to provide and link that back to the problems noted in the question.

(e) A wide range of trends were discussed in terms of adhesives, the chemical industry and also in sustainability. Any two trends from these areas that relate to the example are acceptable, with a basic answer giving a brief description for the trend only and a good answer explaining the trend with more detail. A strong answer will explain the trend clearly and note the potential effect on the example in this question, or link to other examples.

For example, trends may include:

Moving to digital manufacturing may enable better quality control or better control over tailoring formulations to each customer, as with the example discussed in the lectures.

There is a lot of pressure to move to green chemistry solutions in the chemical industry, for both primary and secondary manufacturing. This may lead to pressure to move to new renewable feedstocks, employ catalysts rather than stoichiometric reagents, improve the process monitoring to prevent waste, move to safer solvents and reaction conditions.

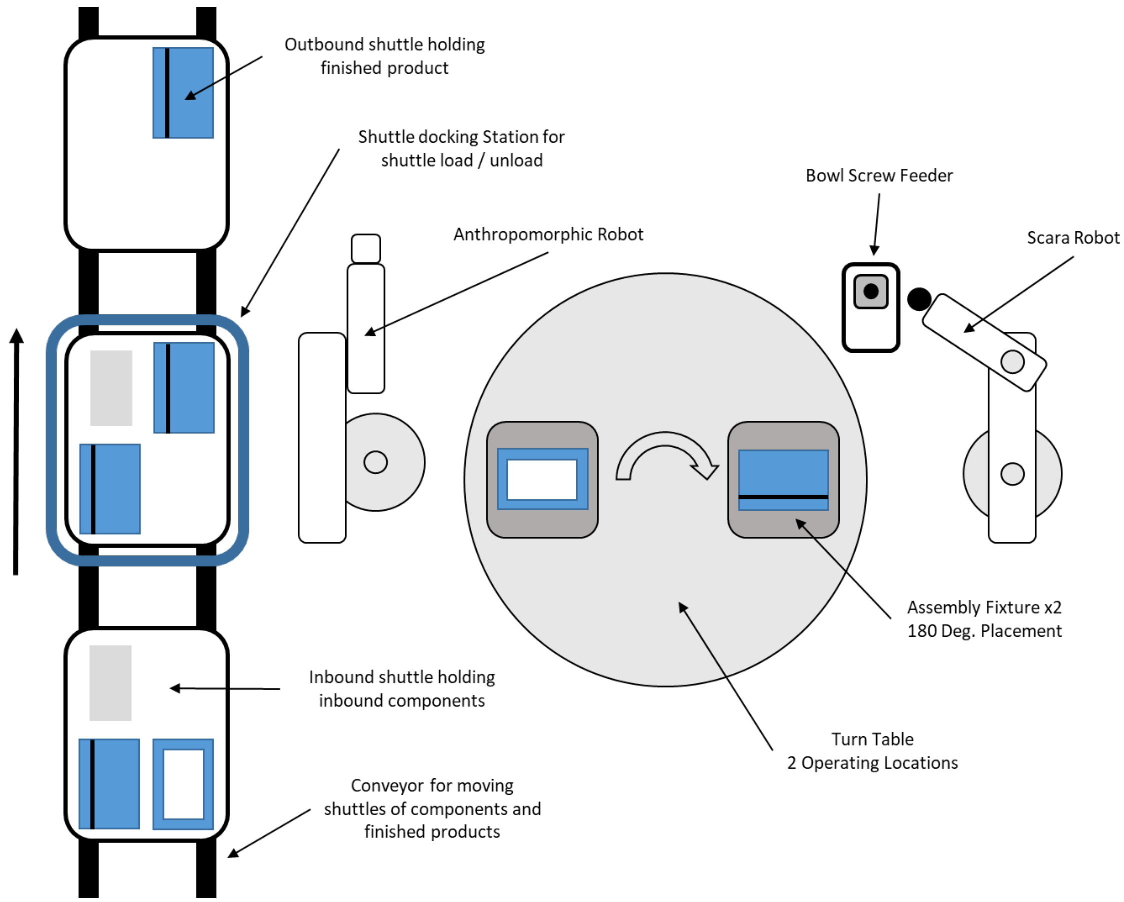
There may be a move to incorporate nanomaterials into epoxies to improve mechanical properties. There will be trends noted by the industrial speaker from Huntsman that will also be acceptable.

In the work on chemical process industry, there were interesting trends regarding a shift from batch to modular continuous systems that may be described here.

It was also acceptable to note a number of trends that were highlighted during the talk on adhesives, regarding a shift to methyl methacrylate adhesives, the need to bond mixed materials, the shift towards adhesives for the transportation sector, the increased demand for products that reduce health and safety hazards and are more eco-friendly.

Question 3

ai) The layout of the automated production system for the all in one computers can be seen below.

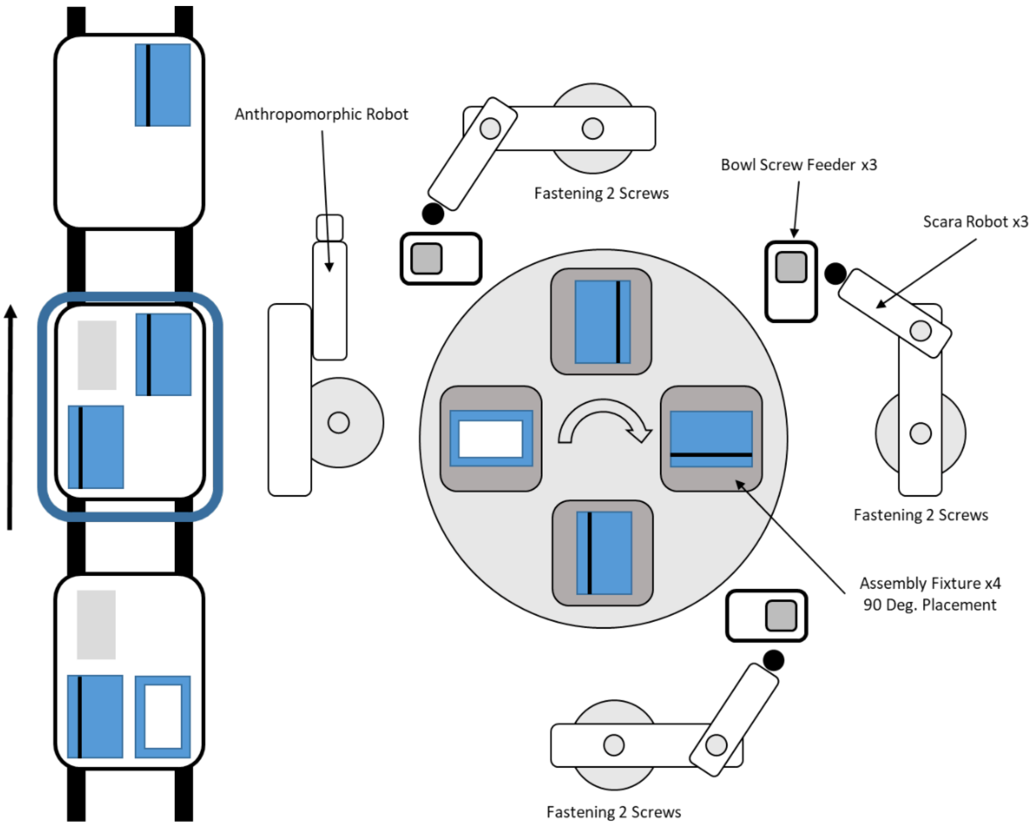


The system would make use of the turntable to rotate two fixtures between each of the robots. With the turntable in one position, a finished computer would be unloaded from a fixture using the anthropomorphic robot and loaded into the shuttle. Three computer components would then be unloaded from the shuttle, assembled and clamped in the fixture. In parallel, the SCARA robot would collect a screw from the bowl feeder and fasten the case and facia together. (This operation would be repeated six times for each of the screws needing fastening.) The turntable would then be rotated through 180 degrees into its second position before previous assembly tasks are repeated.

The conveyor would transport the inbound and outbound shuttles to and from the assembly area. A docking station would locate the shuttle during the loading and unloading process. The shuttles would advance into the docking station. Once a completed computer assembly has been loaded into the shuttle and the computer components unloaded from the shuttle, it would be released outbound.

Equipment	Operation
SCARA Robot	The Selective Compliance Articulated Robot Arm (SCARA) would be used to manipulate the screwdriver and perform the fastening operation. The robot is best suited to this task as it has compliance in the placement of screws and the appropriate stiffness in the Z Axis to accommodate the fastening forces.
Anthropomorphic Robot	The anthropomorphic Robot would be used to manipulate components during the loading, assembly and unloading process. The 5 Axis capability will be important, as the computer case needs to be rotated during the assembly process.
Bowl Screw Feeder	The bowl feeder would be used to hold, align and present screws in the correct orientation required for the screwdriver to load them for the fastening operation.
Rotary Turn Table	The turntable rotates the two fixtures between each of the robots.
Electric Screw Driver	The electric screwdriver is used for loading screws from the screw feeder and performing the fastening operation (Rotating screw to an appropriate torque and fastening depth)

aii) An improved production system shown below provides greater throughput.



Note:

Original System (with constrained resources):

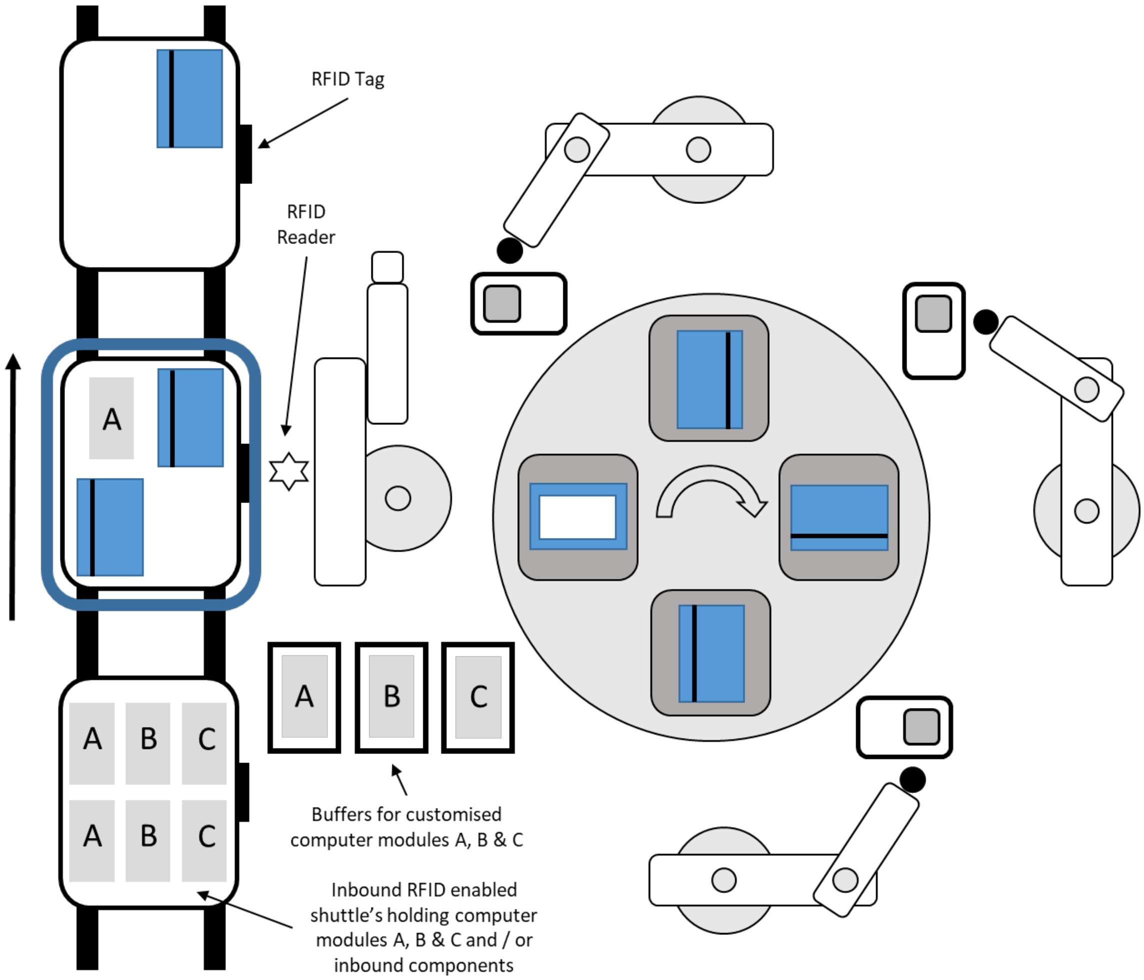
Part Handling Time (Seconds) Anthropomorphic Robot	Part Fastening Time (Seconds) SCARA Robot
Unload assembled computer from fixture 2 Seconds	Screw loading and fastening 6 Screws x 4 Seconds
Load Facia to fixture 2 Seconds	
Load Computer Module to fixture 2 Seconds	
Load Back Case to fixture 2 Seconds	
Total Time 8 Seconds	Total Time 24 Seconds (Bottleneck Process)

System will deliver 1 part ~24 Seconds (Ignoring rotation time of turntable operation)

Improved System (maximise capability of turntable – 4 Stations):

Split Fastening Time across 3 Stations. 24 Sec. / 3 = 8 Sec. (Matching Part Handling Time)
System will deliver 1 part ~8 Seconds (Ignoring rotation time of turntable operation)
[Additional Hardware – 2 SCARA Robots (Fastening 2 Screws), 2 Bowl Feeders and 2 Fixtures]

b) The example production system shown below enables mixed product production using Auto-ID technologies for the tracking of conveyor shuttles and part buffering for different computer modules at the assembly station. In larger production systems, the RFID tag on the shuttle would hold recipe information so that the shuttle can trigger appropriate operations at different production resources across a manufacturing facility.



Additional Technologies:

Hardware / Technology	
Auto-ID (RFID) Tags on Shuttles	Different Auto-ID technologies can be used depending on installation requirements. In this case, RFID is proposed as it provides the most flexibility with both a read/write data capability and an RF communication mechanism. 13.5Mhz passive tags are attached to the shuttle tops allowing the shuttle contents to be represented.
Auto-ID (RFID) Reader at the conveyor docking station	Different Auto-ID technologies can be used depending on installation requirements. In this case, an RFID reader is proposed as it allows the data content of RFID tags to be

	read and updated.
3 Part buffers for the different computer modules	Physical part buffers are required to store and locate the different computer modules until they are needed in a product build.
Adapted shuttle tops for material handling	New or adapted shuttle tops will be required to allow the three different computer modules to be supplied into the system.

Control Philosophy:

The control system would have to be adapted so that different shuttle types arriving or departing the conveyor docking station are handled appropriately. Shuttle types could include; inbound computer modules, inbound computer facia and casing kits to be assembled, outbound assembled products and outbound assembled products with quality issues… The identification of these different shuttle types would be via a data code stored on the RFID tag. On the arrival of a shuttle at the conveyor docking station the RFID tag would be read and the control system would carry out the appropriate operations. The data on the RFID tag could also be updated when a shuttle departs, informing outbound processes of customisations completed or quality issues.

Let us consider some basic operations:

Shuttle Type	Operation
Inbound computer modules (Set task for unloading modules to buffers)	The control system would inform the anthropomorphic robot to unload the computer modules from the shuttle and store them in the appropriate buffers.
Inbound facia and case kits (Specifies the computer module required in the specific assembly)	The control system would inform the anthropomorphic robot to unload the facia to a fixture, select the appropriate computer module from the buffer and unload the case to the fixture.
Outbound assembled product	The inbound and outbound shuttles go out of sequence during the assembly process. It will be necessary to update the data on the RFID tag so that appropriate tracking of customised products can take place.
Extend coding approach for different shuttle types…	

Both the control and motions of the anthropomorphic robot will have to be updated to reflect the inclusion of the buffers for the three different computer modules. The motion sequences would include the movement of parts from the conveyor shuttles to buffers and from the buffers to the assembly fixtures.

Rule sets around the sequencing of inbound shuttles will have to be implemented carefully to ensure buffer stocks of computer modules are maintained with the mix of orders requested.

Question 4

A) Automation can help to replace manual operations in the following areas:
a) Physical operations, b) Data gathering, c) Decision making. The following table provides a list of benefits and challenges that should be considered in the use of automation.

Automation Benefits	Automation Challenges
• Improved working environment for workers. (Reduce tasks requiring heavy lifting or that can cause repetitive strain injuries. Remove workers from noisy, hot or fume laden environments.)	• Complexity of tasks to be automated. (Typically the more different tasks carried out within a process the more difficult it is to automate.)
• Increased production rate / stability. (Ensure products are built at a known and consistent production rate.)	• Production rates to be achieved. (It can be challenging to develop systems to meet high production rates)
• Improved product quality. (Once an automation process has been stabilised it can produce parts / assemblies to a known quality. Appropriate quality checks are normally incorporated into the automation solution.)	• Exception handling. (For every eventuality of a process going wrong an exception handling capability has to be developed, adding further complication to the automation solution.)
• Reduce scrap and rework costs. (As discussed above, once the automation solution is stable it will produce / assemble the correct product first time.)	• Skills required to run production facility. (The implemented automation system will need to be maintained. This can require specialised skills.)
• Improve factory floor space utilisation. (Typically, automated solutions can reduce the floor space needed for its manual equivalent.)	• Payback on automated solution. (Careful consideration has to be made around the payback period of the solution and the life span of the product / process being automated.)
• Reduce manual paper based tracking / scheduling processes. (Automation should not only be considered for physical processes. It can also be used to automate data capture, information flows and ensure salient data is provided as needed.)	• Catering for product change and variation. (If the product or the process being automated is going to change, care has to be taken to ensure that the automation solution will cater for these changes. This can often be expensive and not sensible.)

The company has launched a mechanical ventilator product with growing volumes that may benefit from automation solutions. Care should be taken to ensure that the introduction of automation for these medical devices would not be burdened heavily by regulatory requirements. Care should also be taken to ensure that any automation solutions introduced would not adversely affect the job shop activities and flexibility.

B) Collaborative robots are designed to integrate into manual operations, working safely in close proximity to operators. Programming methods have been simplified to allow non-skilled operators to re-task them quickly to different activities easily.

Collision detection technologies are used on cobot arms so that they can work in close proximity to operators without the need for safety guards. If a collision is detected the arm is brought to a quick stop before any damage occurs. To achieve this the operating speed and payload of cobots is significantly reduced compared to traditional robots.

To simplify the re-tasking of a cobot, they are programmed using a lead through method. An operator physically moves the cobot through its task and the controller records the motion paths.

Cobots can be supplied with an array of technologies to enhance their capabilities. These include; Vision Systems with part identification / inspection, dual arms for assembly operations and integration into automation solutions such as RFID part identification.

Specific Benefits / Limitations for machine tool tendering:

Benefit	Limitation
Flexibility: It will be easy to re-task the cobot to loading / unloading different materials / components.	Speed of operation: Will the cobot be able to operate quickly enough to meet the required cycle times of the machine tool?
Reducing manual operations: The cobot will be able to load / unload materials / parts from / to kitting trays unmanned. (Freeing up operator time).	Weight of Components: Will the payload of the cobot be sufficient to load castings into the machine?
Material Handling: Material handling / logistics are in known and consistent formats.	Skills / Operator Acceptance: Ensuring the correct skills are available on site to maintain and fix the cobot. Acceptance and adoption of the technology by operators. (Flexibility is only achieved through the operators participation!)
Internal vision technologies: These can be used for detecting the presence and location of incoming parts. It “MAY?” be possible to look at the quality of outgoing parts.	Cost / Payback period: ROI needs to be considered.

C) Low cost consumer electronics such as Raspberry Pi's, Arduino's and mobile devices have beneficial capabilities and applications used in the consumer world that are attractive to SME's looking to enhance their production capabilities. (e.g. Face recognition, Audio to text conversion, Image capture and tracking, mobile work instructions…) When using these devices in industrial applications / environments it is important to consider how well they will operate and what would be the impact of their failure. Industrial PLC's are designed to work in harsh environments and fail in known ways, allowing systems to be designed to accommodate these failure modes. Low cost consumer products are not designed or tested to meet these needs.

Industrial applications can be quickly split into two categories; low risk data capture and higher risk equipment control. Industrial surveys have shown that low cost consumer technologies align well to the low risk data capture applications required by SME's. However more work is required to evaluate how robust and secure they will be in control applications.

The following list highlights SME application areas using low cost technologies:

- Real time tracking of jobs (location, status)
- Capacity monitoring of human and machine resources
- Digitised work instructions, photos and assembly procedures
- Automated job scheduling to human and machine resources
- Digital inventory status and reconciliation
- Customer and demand data gathering and analysis
- Display of production schedule around the shop floor

Question 5

(a) (i)

“Clean”: Obvious points are: not contaminated by other materials such as metal or paper, food or other packaging contents. But it also means free from additives, importantly including colouring. Even more difficult is that fact that nearly all polymers include small quantities of chemical additives to improve mechanical or physical properties or to enhance processing, and these are neither declared nor detectable.

“Single polymer”: Generic names of polymers indicate the chemical composition without providing any information about polymer chain length or configuration. This means that additional specifications may be needed for a polymer required for a particular application (e.g. PE for milk bottles which are thin-walled and made by extrusion blow moulding; this requires careful control and dependable material properties).

(ii) Polymers cannot be purified after manufacture. This means that any material separation and cleaning of a polymer that is to reclaimed by mechanical recycling must be done before the polymer is re-melted and extruded to make granules.

Recycling operations normally operate on very small economic margins. Collection, sorting and cleaning are all costly, so there must be a lucrative market for the recycled material. This normally means that the recycled polymer must be suitable for use in high-value products, such as food packaging.

Significance of main factors.

- The more carefully the cleaning and sorting is done, the better the confidence level and the higher the material quality. But this increases costs, so there is a balance to be struck. Economic factors are crucial in a viable recycling operation, so this factor is crucial. For the future, progressive improvements in sorting technologies may be expected to bring down costs.
- Contamination from non-polymers may lead to impaired material manufacturability or mechanical properties (technical). The appearance of the polymer may be changed (discolouring, black spots from decomposition of components) which is often taken to indicate that polymer properties are impaired (which may or may not be the case). The economic value of such material is, however, reduced. Again, this economic factor is crucial.
- Articles manufactured from recycled material that is made from mixed coloured polymers cannot be uncoloured. This may not actually impair their technical properties, but there are many high-value applications that are believed (by customers, by marketing consultants) to require uncoloured polymer, so the economic value of coloured plastic is reduced. Removing coloured plastics from the recycling stream is straightforward with current sorting technologies.
- The main concern about common additives that may be present in recycled polymer is to do with volatile chemicals that are harmful to people. Polymer from uncontrolled sources (mixed household or commercial waste) may easily contain such chemicals, and so recycled polymer made from this material is not suitable for food-grade applications, or for other applications such as baby-care products or anything where the product is used in a confined space. The economic value of such restricted-use polymers is reduced. Tackling the problem basically requires selecting only particular sections of waste streams for recycling, e.g. picking out milk bottles and

using them as the only source of recycled polymer to be used for making new milk bottles (closed-loop recycling).

- Improving packaging design will alleviate some of these problems. Key features are:

  Reduce range of polymers used for packaging, limiting it to easily recyclable polymers (e.g. PET, HDPE, PP).

  Use only single polymers in a particular product, so no mixed polymers (e.g. no multi-layer film).

  Use only uncoloured polymers.

(iii) Reducing, replacing or removing polymer food packaging generally has very negative environmental consequences for all aspects except the avoidance of polymer waste in the environment.

The main effects of polymer waste in the environment are: blocking water bodies, notably causing flooding in Bangladesh which resulted in the first plastic bag ban); effects on marine and terrestrial life (including entanglement; suffocation etc, mistaken for food so causing starvation); microplastics (including entering the food chain particularly from marine environment; consequences not yet fully understood but what evidence there is suggests far-reaching effects).

The efforts of the packaging industry (and that of many leading retailers such as Tesco and M&S) to improve environmental responsibility are very badly hindered by the 'zero plastic' movement.

- Cardboard box has greater environmental footprint than PET clamshell. There's a lot of processing involved in manufacturing cardboard. Compared with the equivalent plastic packaging the carbon footprint is typically 4x higher; 60% more water used; 50x more waterborne pollutants, 70% more airborne toxic emissions. And likely to be heavier, so just uses more material. However, cardboard can be composted at end-of-life. Mechanical protection should be equivalent. Barrier function less good, so shelf-life may be reduced and food wastage increased. Environmental burden of food production dominates that of packaging (typically packaging might contribute 1% to total carbon footprint), so avoiding food wastage is very important.
- Glass is much heavier than PET so material burden is high; both materials require high energy to produce. Transport costs significantly increased (secondary factor): weight of bottles, significant reduction in packing efficiency in vehicles (may be threefold increase in number of vehicle loads required). Glass recycling rates high, and there is environmental benefit if the glass is re-used for bottles, but unless it's clear glass then it will have been downcycled. PET is energy-efficient for this application, and PET is readily recycled at end-of-life.

Cucumber wrapping: LLDPE shrink-wrap contributes a few % to the carbon footprint of the product: most of the environmental impact comes from agriculture (growing the cucumber) and transportation. The shrink-wrap protects the cucumber against mechanical damage (so more of the product reaches the consumer in edible condition). It also prevents water loss, so increasing its shelf-life from 3 to 14 days, thereby significantly reducing food wastage. Avoidance of food wastage should dominate the environmental discussion.

(b) Use of a biodegradable polymer for food packaging where the packaging is contaminated by food does have some apparent merits, but this can only be realised if supported by waste disposal infrastructures, which is not generally the case currently.

Use of a disposable, single-use container is environmentally questionable, even if the container can be recycled or composted.

PLA has physical properties similar to polystyrene, can be modified to resemble PE and PP and has grease resistance comparable to PET. It is suitable for food packaging and is used for food and medical applications. The market share for PLA is currently growing faster than any other biopolymers. However, note that bio-based polymers are in total only about 2% of the polymer market, so cannot provide a big enough proportion of polymer production and usage to make significant impact.

Only about half of biopolymers are biodegradable; PLA is biodegradable (by hydrolysis) in most formulations.

PLA is produced from bio-based sources: from maize, predominantly.

LCA analysis shows that environmental burden may be greater for PLA than for petrochemical-derived polymers:

Biopolymer feedstock (maize) requires intensive agriculture, carrying environmental burdens from energy (e.g. farm vehicles), agrochemicals (fertilisers, pesticides), water (irrigation). Many of these aspects make extensive use of fossil resources.

Manufacture of the bio-based polymer is just as energy-intensive as manufacture of polymers from petrochemical sources.

End-of-life environmental impacts are problematic. PLA can't easily be separated from other non-biodegradable polymers, so is normally rejected from both composting and recycling waste-streams. Biodegradable polymers may be compostable and may degrade in commercial facilities, but most commonly they go to landfill or at best are used for energy-from-waste. If they end up as litter, they are likely to degrade only slowly, and so may still contribute to visible plastic waste.

The environmental justification for the claims is therefore very questionable.

Answer standards:

Basic answers: Demonstrate understanding of the underlying technology of recycling and its environmental justification.

Good answers: Good depth of knowledge and understanding. Appropriate examples discussed with accuracy.

Excellent answers: Detailed descriptions and analysis. Demonstrate understanding of the more subtle tensions in the environmental assessments.

Question 6:

1 (a) (i) State the different ways in which constraints can be set in optimisation problems. [10%]

Answer: Constraints define the extent to which decision variables can be changed. There can be inqeuality and equality constraints, the latter of which are more difficult to handle and needs to be avoided if possible. These can be "relaxed" by converting them into inequality constraints. Another constraint relaxation method could include making the solution feasible but applying a suitable penalty to the solution obtained. A basic answer to this question will mention types of constraints, better answers will mention constraint relaxation and detail them.

(ii) Briefly describe the different approaches for optimising more than one objective? [10%]

Answer: One can keep one objective as a constraint and the other as an objective function, rerunning the optimisation multiple times to obtain the efficient frontier. Another method would involve representing them in one function, the advantage of which is that different weightings to objectives can also be added. Two objectives could be simultaneously optimised using a suitable multi objective algorithm solver such as an Evolutionary Multi-Objective Algorithm.
A basic answer to this question will mention the constraint method, better answers will mention simultaneous optimisation, suitable methods, and their advantages.

(iii) Discuss how the performance of heuristic optimisation approaches can be evaluated. [10%]

Answer: As heuristic methods do not guarantee an optimal solution, and solutions differ between different runs, a suitable number of runs (suggested min. 50) should be determined and the average best solution and its standard deviation between multiple runs should be obtained. If the starting point effects convergence, multiple starting points should be experimented with.
Other performance metrics could include the time taken to reach convergence or the final solution after a pre-specified cpu time. A small sample with known optimality can also be experimented with.
Advanced answers may also mention performance of heuristic multi-objective algorithms, where solution diversity and objective search space coverage is also taken into account.

(iv) What is the role of "archiving" in multi-objective optimisation approaches? Briefly discuss different approaches to archiving. [15%]

Answer: Archiving is the process of storing high performance solutions between iterations so as to speed up solution search and prevent being stuck in local optima. Rudimentary archiving may include storing a number of best solutions for example.

However the solutions may be very similar and may not inform the engineer on the search space itself; so best n solutions with a minimum level of dissimilarity may be stored instead (here a suitable metric for determining dissimilarity needs to be designed). A probabilistic method may also be applied to archiving close-to-best solutions. Adapting any stochastic optimization algorithm to perform multiobjective optimization will inevitably require a common change to the method of archiving. In multiobjective optimization solutions lying on the trade-off (non-dominated) surface will be archived but domination of previous archive members need to be taken into account which will increase algorithm complexity.
A basic answer to this question will mention basic archiving process of storing best solutions and why it is done, better answers will discuss additional information detailed above.

(b) Kelly's Wheels is a bicycle supplier in the UK and has obtained data related to predicting their sales from a survey of customers. Kelly's Wheels thinks that the most significant factors affecting sales are the following:

- *Price level*, which is the perceived level of price charged by product suppliers;
- *Overall service*, the overall level of service necessary for maintaining a satisfactory relationship between supplier and purchaser;
- *Product quality*, the perceived level of quality of a particular product.

Respondents to the survey provided a numeric rating between 0 and 10, with 0 being "poor" and 10 being "excellent". Based on the data, Kelly's Wheels developed a multiple regression model for predicted sales level , for which the summary output is shown in the figure below.

(i) Based on the summary output, estimate Sales level of a particular customer who has rated Price level, Overall service, and Product quality as 3, 4, and 5 units, respectively. [5%]
Answer: When X1 = 3, X2 = 4, X3 = 5, Y = 55, a 95% CI is [Y-2 x Sterr, Y+2 x Sterr] = [43.85.00, 67.02].

(ii) Discuss whether this model is acceptable as a means of predicting Sales level. Explain the rationale for your answer. [10%]
Answer: Students should check the R-square and adj.R square statistic, standard errors, p-values and confidence intervals. P values are high for Service level and Price level, whereas they are not for Quality level. We need to re-do regression by dropping Quality level. Good students will also mention that coefficient signs are in alignment with expectations. Some will mention that we are bound by data and the

Regression Statistics	
Multiple R	0.773
R Square	0.598
Adjusted R Sq.	0.585
Standard Error	5.79
Observations	100

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	4781.700	1593.900	47.541	6.40E-19
Residual	96	3218.556	33.527		
Total	99	8000.256			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	19.475	4.048	4.811	0.000	11.439	27.511
Price level	-3.083	0.697	-4.426	0.000	-4.466	-1.700
Overall service	10.944	0.980	11.163	0.000	8.998	12.890
Product quality	0.288	0.452	0.638	0.525	-0.609	1.185

Fig. 1

model may not handle variations outside the sample range. Others may point to the need to see randomness in residual plots (which are not shown here).

(iii) What is the impact of an increase of two units in Product quality on the Sales level? [10%]

Answer: The impact of one unit increase in Product quality level is 0.288, and with a 95% CL, the impact on Usage level is between [-0.609, 1.185]. So the impact from two units increase in Product quality is 2*[-0.609, 1.185] = [-1.217, 2.370].

(iv) Can the relative importance of explanatory variables be established from the coefficients in this model? Is your answer applicable to any regression model? [15%]

Answer: Coefficients represent the slope of the linear relationship between the Independent variable and the dependent variable (that is Independent of other predictor variables). Positive values indicate a positive relationship with the dependent variable and negative values indicate a negative relationship with the dependent variable. Although generally it is said that the large coefficients are more impactful, for coefficients to be truly comparable the unit of analysis and the range of values should be the same (one way to achieve this would be to standardise data before regression). In this case they are, so they are indeed comparable.
A basic answer to this question will define what a coefficient is and how its sign may be interpreted. Better answers will mention cross-comparability and standardisation.

(c) The financial return of a new product development project is believed to be normally distributed with a mean of 1% and standard deviation of 2%. Find the probability that the return will be at least 3%. [15%]

Answer: We know that in a standardised normal distribution mean is zero, and the area between +/- 1 standard deviation of the mean is 68%. Since normal distribution is symmetric around the mean, the probability of obtaining a positive return of one standard deviation will be 16% (obtained by (100-68)/2). Instead here we have 1% return as the mean and 2% as the standard deviation. Hence the probability of getting a return $x \geq (\mu + \sigma) = (1\% + 2\%) = 3\%$ will be 16%, and so will getting a negative return of -1% (i.e. 1%-2%=-1%). At the 95% C.I. this would be obtaining a +5% return and -3% return each of which will have a probability of 2.5%.

Students will progressively get more marks for demonstrating knowledge to perform the calculation correctly.