METIIB, Paper 1,

Question 1

1(a) (i)

Detailed descriptions or brief descriptions supplemented with diagrams of the process were acceptable. A good answer would include points on the input materials and clamping, injection, cooling and ejection. A very basic answer would note something about the input materials and describe the injection part but detail was required in terms of the importance of pressure, runners and shot size for this to be acceptable.

An excellent answer would include a note on:

- Plastic granules being loaded into a hopper
- The screw within a heated barrel forcing the polymer towards the nozzle.
- The clamping of the mould cavity and the mould.
- The injection of the molten polymer (details about runners and shot)
- The cooling of the mould
- The ejection of the component (including the potential use of ejection pins for example)
- Many people also included a comment about the final removal of the sprue and recycling of waste back into the process, which were excellent additional points.

Any appropriate examples was acceptable if they were clearly showing this is a production process for use with high volume production because of the high tooling cost and capital investment. Typical applications noted were dashboards in cars, covers in consumer electronics and household products such as many plastic lids for fast moving consumer goods, such as shampoo bottles, etc.

1 (a) (ii)

There are a range of quality issues that could have been discussed. An excellent answer would give the correct term for the type of quality issue or defect, explain the defect/issue in detail and then note the likely causes. The difference between good and excellent answers was the clarity of the descriptions and the level of understanding conveyed. Descriptions or detailed examples were both acceptable ways of showing this understanding.

Example defect/issues noted included:

Flow lines - These are lines or streaks, normally a darker shade than the surrounding plastic. This is due to the flow path and cooling during injection into the mould. The flow changes direction and speed when flowing around features and especially sharp corners. Solidification occurs at different speeds across the cavity when the injection speed is too low.

Knit lines/Weld lines: This appears as a discoloured line, where molten plastics meet as they flow from different parts of the mould. The flow fronts do not bond correctly, most often due to partial solidification.

Sink marks: Depressions on one side of a component due to the thicker section or a large feature on the other side. These thicker areas shrink upon cooling to give the depression. The cooling time needs to be sufficient to allow cooling in the mould.

Warping: A deformation or bending where there is uneven shrinkage across the component. This is usually due to uneven cooling across the material. Different cooling rates or rapid cooling leads to internal stresses.

Flash: If the clamp force is not sufficient, the mould/die are not precisely manufactured, the mould/die are worn or corroded or if the injection pressure is too high, there will be a leak of the polymer around the join leading to flashing.

Other valid defects/quality issues were accepted.

1 (a) (iii)

For each technique chosen, marks were assigned for a really basic description of the technique, with additional marks allocated for details about the technique or format of output results. Similarly, marks were allocated for a basic property found with the technique and additional marks for multiple properties of a very clear description that showed an excellent understanding. It was very important to include in the answer the expected results "in this case", described in the question. This seemed to differentiate those who had memorised the technique, and those that could hypothesis about the likely results based on the problems seen in the example polymer.

An excellent answer would note that this is a semi-crystalline polymer and so we should examine the level of crystallinity, and that this will have an effect on mechanical properties. In addition, because molecular weight also has an effect on modulus, the molecular weight distribution should be compared with previous batches. It would be good to identify if there are any contaminants present leading to a change in mechanical behaviour.

Examples of characterisation techniques that could be discussed include:

Differential scanning calorimetry (DSC). The amount of energy needed to increase the temperature of a sample is measured. This detects phase transitions because of the quantity of energy needed to change temperature. The glass transition temperature can also be observed. Also, the percentage crystallinity can be defined.

Gel permeation chromatography is a separation technique. The columns contained insoluble beads with a rigid pore structure. The pores can exclude very large molecules, allow partial permeation of medium sized polymers and allow total permeation of smaller molecules. The larger molecules therefore don’t have a long residence time in the column and flow through. This means the polymers are separated with the largest coming out first and smallest last. The full molecular weight distribution can be defined and compared with previous results to see if this is influencing the mechanical behaviour.

A range of spectroscopy techniques can be discussed, including UV/Vis, FTIR or Raman. FTIR is often used to examine potential contamination. However, a good initial examination of contamination is with thermogravimetric analysis (TGA). This thermal technique measures the rate of change in mass as a function of temperature. This can identify changes in the oxidative stability and the composition. This is a highly sensitive technique and any contamination would be immediately highlighted. This technique is often used to identify the percentage of filler in a polymer sample, which also effects the mechanical properties.

It is expected that the crystallinity may be lower than expected, the molecular weight may be lower than expected and there may be contamination in the batch.

1 (b) (i)

An understanding of the basic definitions was expected to be conveyed. For example:

Primary industries convert raw materials into a primary form.

Secondary industries convert primary products into final products

However, the majority of the marks were allocated to the detailed description requested in the question, by noting and explaining characteristics and including examples. For the primary industries, examples included base chemicals, petrochemicals & derivatives (formed by cracking, distillation), basic inorganics (sulphuric acid, sodium hydroxide) and fine chemicals.

There are many different characteristics that could be discussed. The most commonly noted include the fact that the plants tend to be large & integrated, capital intensive and the products are generally commodities. Large efficient plants dominate, and the innovation rate is necessarily low. The supply chains are often vertically integrated, and the volume and mix are stable and/or predictable.

Examples of secondary industries include speciality chemicals (paints, inks, dyes, crop protection) and consumer chemicals (detergents, soaps, toiletries). Example characteristics include high velocity supply chains, with rapid product and process innovation. The mix and volume are usually volatile. Both automation and people skills are required in manufacturing.

Excellent answers can distinguish on a range of factors including competition, innovation, markets, plant and supply chain complexity.

1. (b) (ii)

A basic answer would note a couple of reasons why a move away from purely batch manufacturing is required by the pharmaceutical industry, a very brief description about one alternative and 2-3 reasons why this alternative would be advantageous. An excellent answer would add more detailed descriptions and analysis.

Batch is very versatile but extremely slow and not very precise. There is approximately a 2-year timeframe from the start to the end of the process development (primary manufacturing part only). The level of noise in terms of quality control is also quite high compared with other approaches. This approach requires capital intensive investment very early in product development to allow the running of clinical studies. However, this same process needs to be able to ramp up to full production. There is therefore a very high cost associated with failure. The batch approach is also not very agile to deploy around the world and leads to centralised manufacturing, whereas local production and distributed manufacturing may be important for future cost reduction. In batch manufacturing, it is difficult to reconfigure or change the design and this again adds to the cost of the products.

One approach being examined is substituting a number of the batch steps with a continuous process. The approach requires the design of a modular continuous manufacturing plant. This building-block approach allows reconfiguration, agility to deploy, agility to re-use in other processes if the product fails, the benefit of the precision and higher levels of automation achieved in continuous manufacturing and the ability to build closer to the point of distribution rather than have large centralised manufacturing sites. Each module is a unit operation and these savings will be realised even by replacing a sequence of a few of the batch steps.

It may be noted that pharmaceutical companies are risk averse about moving the entire process to continuous manufacturing because of the challenge of controlling crystallisation and the significant knowledge currently in place that surrounds batch processing in this field.

Question 2:

(a) (i) It was expected that the candidates would provide two different AM example techniques, describe their basic method of operation before providing more detail about the operating parameters, capabilities and also a schematic where it helped to show a detailed understanding. Very strong answers were able to provide this level of detail for both techniques chosen. Example applications were expected for each technique. Excellent answers could identify why the particular additive technique noted may be chosen over conventional production technologies. General advantages of additive manufacturing were also accepted.

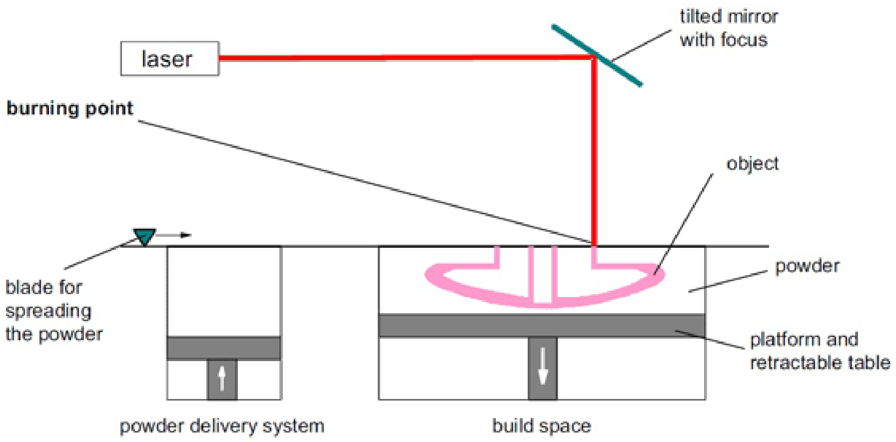
Example details are given below:

Almost every powder-bed based AM system uses a powder deposition method consisting of a coating mechanism to spread a powder layer onto a substrate plate and a powder reservoir.

Usually the layers have a thickness of 20 to 100 µm. Once the powder layer is distributed, a 2D slice is melted using an energy beam applied to the powder bed. The energy source is normally one high-power laser, but state-of-the-art systems can use two or more lasers with different power under inert gas atmosphere.

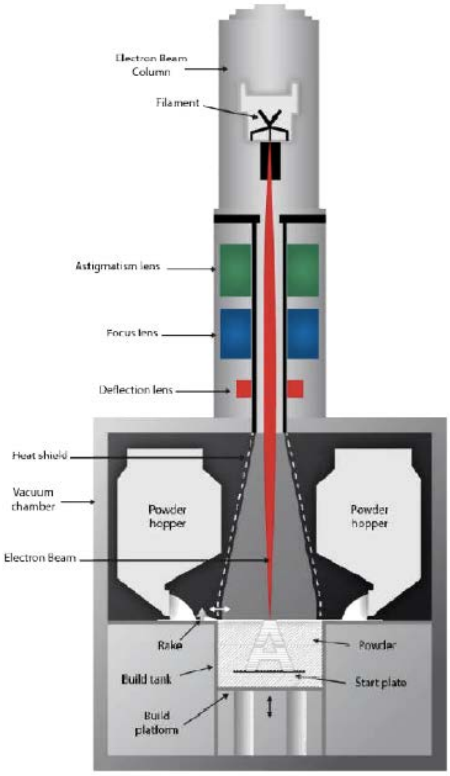
Direct process powder-bed systems are known as laser melting processes and are commercially available under different trade names such as Selective Laser Melting (SLM), Laser Curing and Direct Metal Laser Sintering (DMLS). The only exception to this process principle is the Electron Beam melting (EBM) process, which uses an electron beam under full vacuum.

The melting process is repeated slice by slice, layer by layer, until the last layer is melted, and the parts are complete. Then it is removed from the powder bed and post processed according to requirements.



- Laser based AM allows you to address a broader range of components with up to 150 cm³/hour deposition rate, significantly improves productivity
- Intelligent gas flow ensures the efficient removal of process emissions and extends filter life
- Single additively manufactured galvo mounting built in AlSi10Mg with internal conformal cooling fluid channels enables excellent thermal stability of the optical system
- Build volume 250 mm x 250 mm x 350 mm
- Integrated sieving and powder recirculation

Another example being Electron Beam Melting, as supplied by Arcam.



The electron beam gun generates a high energy beam (up to 3.000W)

- The beam melts each layer of powder metal to the desired geometry

- Extremely fast beam translation with no moving parts
- High beam power -> high melt rate (up to 200 cm3/h) and productivity
- Vacuum process -> eliminates impurities and yields excellent material properties
- High process temperature (650 ºC for titanium) -> low residual stress and no need for heat treatment

There are many examples of products. One possible example would be implants (Stryker AM). Stryker's Titanium PL Cage is a hollow, rectangular implant that consists of a unique configuration of both solid and porous structures, which are simultaneously built using 3D Additive Manufacturing applying Stryker's proprietary Tritanium In-Growth Technology. The Tritanium PL Cage demonstrated better resistance to subsidence than other commercially available posterior lumbar interbody cages constructed out of different materials, including those with a larger footprint. These geometries could not be produced by any other means. Stryker are focusing on 80% of their parts being manufacturing by 2020 by AM technologies

Another example using e-beam is the production of turbine blades (Avio SpA, Italy). In this case the benefit is increased production rate.

Production case for aerospace:

- Turbine blades in TiAl
- Prototype turbine blades in TiAl
- 325 mm build height
- Dimensional tolerance: 0.1 mm
- Turnaround time: 7.5 h / blade

(a) (ii) This question was again answered very strongly, showing very good understanding of the challenges in metal additive manufacturing and why it does not translate to high volume manufacturing. Good answers gave 2 challenges and 1 innovation, explained very clearly with examples. Excellent answers discussed additional challenges and innovations.

Some example details are included here:

There are many AM technologies currently employed to produce metal parts. The majority of systems employ lasers as the principle energy source. Figure.1 shows the current state-of-the-art in terms of build rate against power for commercially available AM technologies. Many systems operate at low power (< 1kW) due to the technical difficulties of using multi-kilowatt single point laser scanning technology and the associated melt dynamics that cause melt flow instabilities at high scanning rates, particularly with multi-kilowatt lasers. One can see there is a strong correlation between build rate and laser power. The data presented here for metals suggests that it requires 100 W of laser power to build at a rate of 4 cubic centimetres per hour. It is clear that current systems whilst capable, are not meeting the expectations of industry for higher build speed. However, increasing build rates cannot be delivered by simply increasing the power of single point scanning systems since there are a number of problems associated with high speed melt production such key hole effects, melt pool instabilities, and residual vaporisation. Those systems that do provide higher build rates, such as the SLM solutions 500, employ higher powers through multiple scanning heads, with 4 heads being employed in the case of the SLM 500. The consequence of employing multiple is scanning complexity and cost. An order of magnitude increase in build rate requires an order of magnitude increase in power since, notwithstanding the time penalty of powder deposition, power is the direct driver of build rate for any AM system. Figure.2 presents data on the price of current commercial AM systems against laser power (prices as of June 2016). This data suggests a price-power relationship of $140,000 per 100 W of laser power.

(It is only expected that the candidates can note the general trend of the data, not the detailed graphs.)

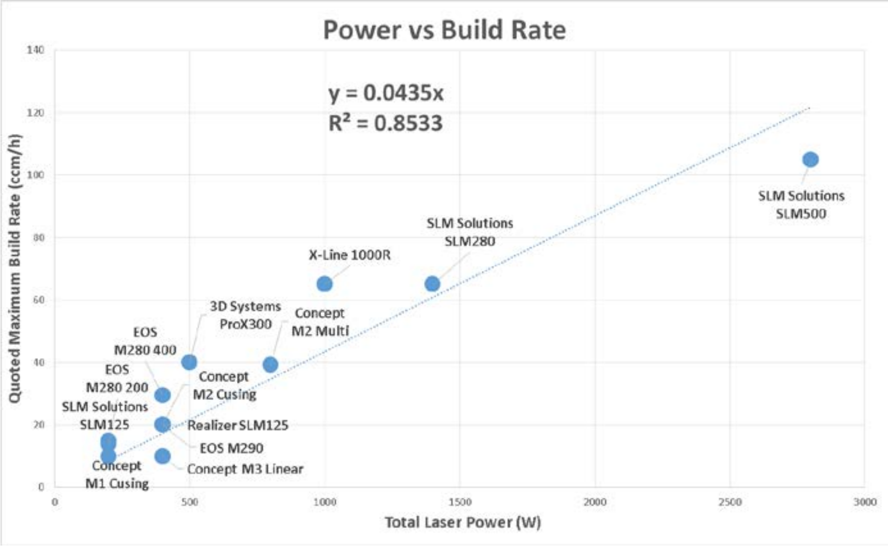


Figure 1 Build rate (cm^3 hr^{-1}) against laser power for commercial metal-based AM systems

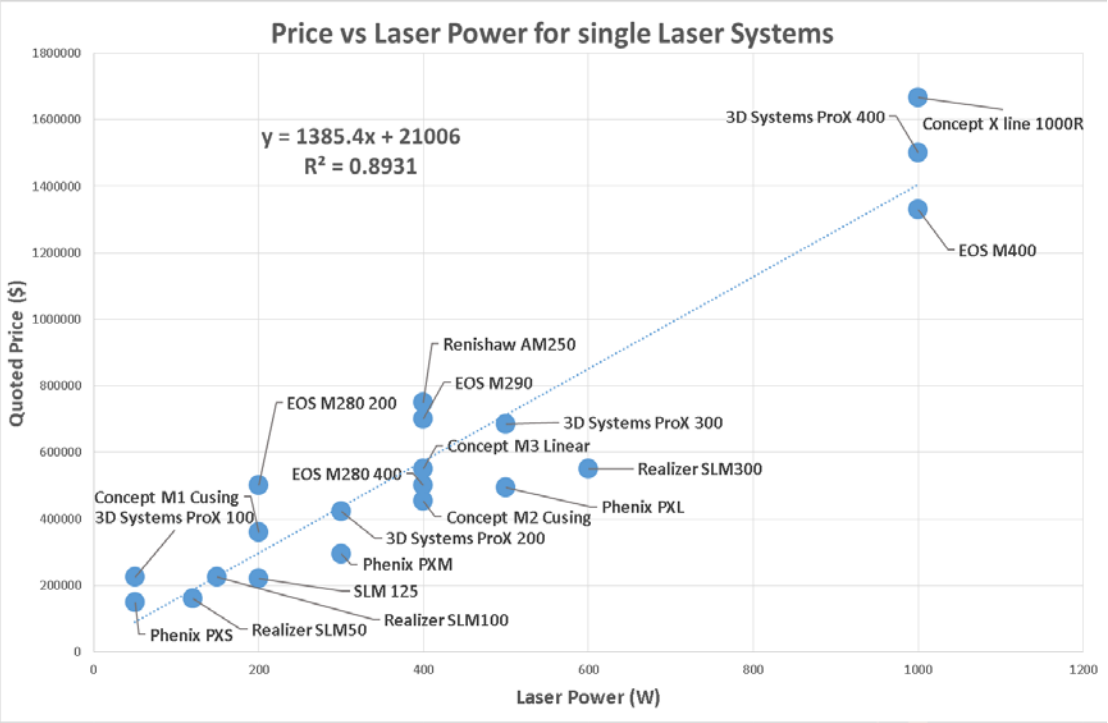


Figure 2. Price against laser power for current AM systems.

Considering the position of the current state-of-the-art AM technology, increasing build rates by two orders of magnitude from 4 cm^3 hr-1 to 400 cm^3 hr-1 would require a stepwise power increase from 100 W to 10, 000 W. Applying the price-power relationship of Figure.2 would project a system price of $14,000,000. This cost is clearly untenable. Whilst cost reduction could be applied in future systems, the likelihood of current technology delivering x100 increase in build rates is extremely low. This rather simple analysis effectively highlights two fundamental issues in the AM industry. Firstly, all current metal-based AM systems are based on technology concepts that are around 16 years old and have experienced incremental advances in this time (moderate power increases or multiple scanning systems). Secondly, the growing expectations of AM technologies by future users, i.e. build rates, cost, and quality, are currently in excess of the AM suppliers' ability to deliver using current platform concepts.

There were a range of innovations discussed in lectures regarding reduction in cost, increase in throughput through laser arrays and increasing laser power, these and other valid suggestions were accepted.

(b) (i) This question did not specify a specific number of similarities or differences required in the answer, and so either were accepted (e.g. all similarities, all differences, any mix of the two). A basic answer would explain two in detail, whereas the outstanding answers included 4-5 points. Some examples are included below.

Semiconductor fabrication, like AM technologies, apply material in layers. AM technologies have in some respect borrowed their techniques from semiconductor fabrication. Whilst the number of layers in semiconductor processes are relatively few, the number of steps per device is very high (several hundred). Since these involved the deposition of base materials such as resists (curing steps), alignment of masks (a significant overhead cost), photo exposure, planarization (removal steps), metallisation (for interconnects), oxidation and the process repeated for interconnects, and insulating layers. The process is much more complicated than AM techniques, although the parallel production methods, and high resolutions (nm) makes the process very efficient. On the other hand, AM techniques invariably use a single material, with lower resolution (um), and many more layers (1000s rather than 10s of layers). The bigger parts that are produced in AM and therefore built far more slowly. We have many types of AM production technologies, although most are not useful for high volume manufacturing. The biggest issue is that most additive fabrication techniques are serial so larger areas take more time. Contemporary AM is for components with sizes ranging from mm (or submicron) to a metre or so.

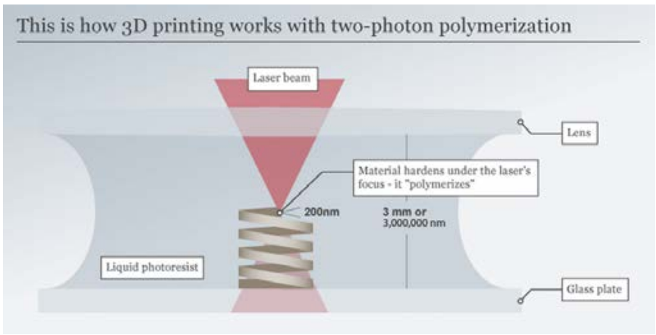
Processes for semiconductor manufacturing deliver resolutions in the nm range, 15-45nm, with EUV techniques offering 7.5nm resolution. Currently, mask-based lithography is the norm. Researchers are investigating, e-beam, maskless, and nanoimprint lithography. In all of these techniques, printing is done vertically on horizontally placed semiconductor wafers.

(b) (ii)

Marks were allocated for this answer based on the level of understanding conveyed of each emerging technology. Significant marks were available for a brief and basic description, but a real understanding was shown by noting some details about the process characteristics, possibly a schematic or through better explanation through examples.

Possible processes are noted below, but valid alternatives were also accepted:

Nanoscribe: This process employs two photon photolytic techniques and high resolution positioning. The laser beam itself has a computer-controlled beam guidance system that translates a 3D CAD model directly into 3D structures of almost any complexity at any scale. Essentially it can fabricate microstructures as small as 500 nm, including those with complex geometries and support structures, at extremely high resolutions (100nm with reports of new materials reaching 45nm). The 3D printing technology that Nanoscribe developed has allowed sub-micron parts to be fabricated with geometries and internal structures that would be completely impossible to create using standard micro-scale manufacturing techniques.

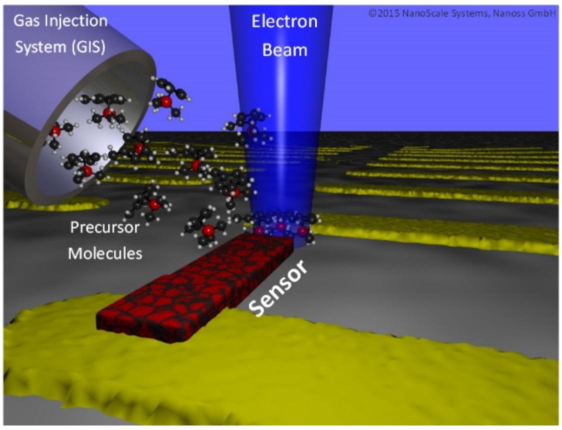

This is how 3D printing works with two-photon polymerization

Process performance is given as

Specifications		
objective 63x, NA=1.4	galvo mode	piezo mode
3D lateral feature size (IP-Dip)	≤ 200nm; typically 160nm	≤ 200nm; typically 150nm
2D lateral resolution (IP-Dip)	≤ 500nm; typically 400nm	≤ 500nm; typically 300nm
vertical resolution (IP-Dip)	≤ 1500nm; typically 1000nm	≤ 1000nm; typically 800nm
range	Ø 200µm (140x140µm^2)	300x300x300µm^3
writing speed	typ. 10mm/s	typ. 100µm/s
accessible writing area	up to 100x100mm^2	up to 100x100mm^2
Femtosecond fiber laser		
maximum laser power	≥ 120mW	
laser center wavelength	780 ± 10nm	
laser repetition rate	80MHz	
Software package		
NanoWrite, DeScribe		

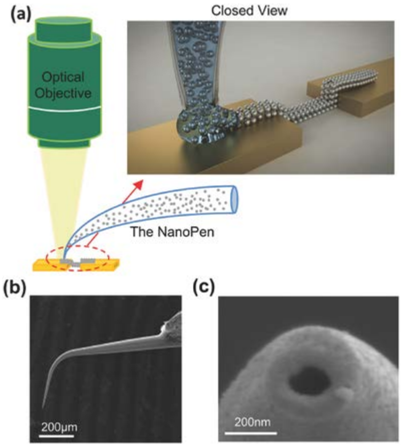
Nano3Dsense

3D Nanoprinting can be employed in a conventional SEM that is adapted to employ e-beam deposition of materials from the gas phase. A highly focused electron beam with a diameter of a few nm is employed as an ultra-small "pen" for the layer-by-layer production process of structures. Very small dimensions as low as 10nm are achievable, on almost all material surfaces or geometrical shapes. The system operation is shown in the figure. Its application is focused on the maskless fabrication of chemical, and motion sensors, without the need to employ conventional lithographic techniques



Fountain pen nanolithography (FPN).

FPN is a printing method, which, utilises a reservoir filled with nanoparticulate ink. These ink solutions can undergo nanochemical changes during the lithography process, resulting in the desired functional lines and structures. Line width control from 15 nm to over 1000 nm have been demonstrated. Line produced showed micrometer lengths, consistency of line dimensions, precise placement, and conductivity. Similar to the reservoir in fountain pens, the nanopipette reservoir enables numerous lines to be printed without refilling. This technology could be expanded to the production of conductors and actuators, correction of flat panel displays, and mask repair applications.



Fountain pen nanolithography system. a) A diagrammatic representation of the FPN process depositing a nanoparticle dispersion to connect metallic lines. b) The structure of the probe as seen in a scanning electron microscope (SEM) image. c) An image of the nano pen aperture.

Examiner’s Comments:

Question 1:

This was a very popular question choice, taken by all but four of the group. Almost all candidates showed good or excellent knowledge and understanding of at least one part of the first question. This covered two very different areas of production technologies and materials, firstly the topic of injection moulding and polymer analysis and secondly two aspects of the chemical process industry.

While part (b) was answered slightly more successfully than part (a), this was due mainly to 1(iii), which was found to be the most challenging. However, overall a very good level of understanding was shown. The differentiation across the cohort appeared to reflect the difference between memorising material and being able to apply it to the example given in the question.

Question 2:

This was again a popular question to attempt, with 63% of the class completing an answer. Question 2 was focused on additive and ultra-precision manufacturing. All candidates showed good or excellent knowledge and understanding of at least two parts of the question. Part (b) was answered less successfully than part (a). The differentiation across the cohort in Part (a) came from the level of detailed understanding conveyed about the techniques and their most important parameters, as well as the level of understanding about why additive manufacturing was chosen for the examples discussed. In Part (b) the differentiation came from the range of points that were identified and the level to which they were explained.

Question 3

A mobile phone manufacturer currently assembles two models of phones on a manual production line. One particular operation involves the fastening of all components to the inside of the front phone cover using self-tapping torque screws. The production manager for the area has been asked to investigate the use of a robotic fastening cell to replace the current manual operation.

a) Discuss the pros and cons of different robot types that could be used within the fastening cell. Rank the suitability of each of the robot types discussed.

[30%]

b) The systems integrator building the robotic fastening cell is going to develop an end-effector that can be fitted to the end of a robot. The end-effector will accommodate the operation of a simple electric screwdriver to perform the fastening of the self-tapping torque screws. A diagram of the electric screwdriver can be seen in Figure 2. The electric screwdriver has the following features to support fastening operations:

a. Two forward rotation speeds; slow speed and screw fastening speed.
b. A mechanical motor clutch to limit the torque applied during screw fastening.
c. An output contactor that changes state when the mechanical motor clutch engages.
d. A vacuum port to enable screw pick-up.

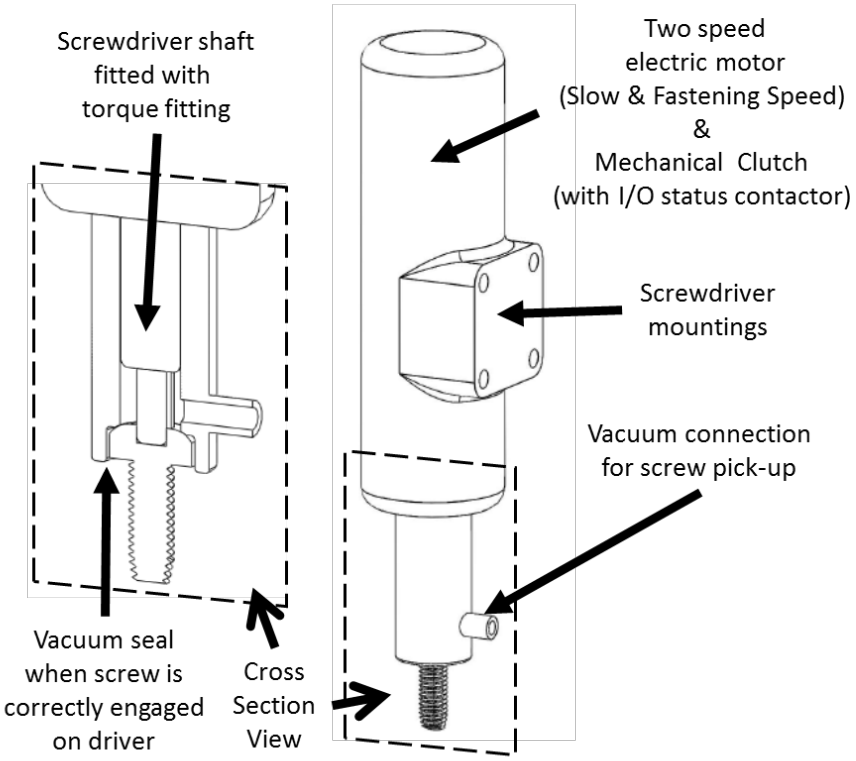


Figure 2. Electric Screwdriver

(i) An end-effector is to be designed to facilitate the operation of the electric screwdriver when mounted onto the robot. Specify the type and location of actuators and sensors that would be required to perform fastening operations. Indicate how the sensors you select can be used to identify common error conditions.

[40%]

(ii) Draw a flowchart that depicts the logic required to control the operation of the robot, end effector and screwdriver when performing all actions required to fasten a screw. Include on the flowchart the logic associated with any error conditions that should be considered.

[30%]

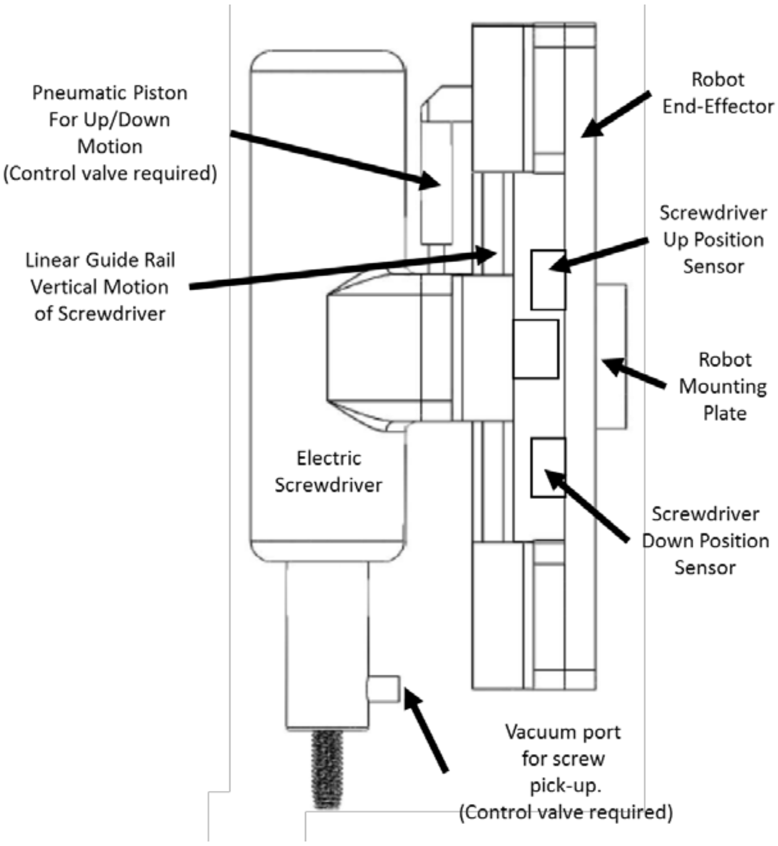
ANSWERS (MSE)

a) Discuss the pros and cons of different robot types that could be used within the fastening cell. Rank the suitability of each of the robot types discussed.

Robot Configuration	**Pros**	**Cons**	**Rank**
Selective Compliance Assembly Robot Arm (SCARA)	1) Selective Compliance Assembly Robot Arm is an ideal robot type for inserting screws into holes. Stiff in the Z Axis but compliant in X,Y. 2) Due to its stiffness in the Z axis it can apply significant loads in the Z axis. This is essential when inserting self-tapping screws. 3) The SCARA robot has the best repeatability of the different robot types on the market, making it ideal for the placement of small screws in an electronic assembly. 4) The SCARA robots are some of the fastest robots on the market, allowing it to easily service operations from the two lines and a screw feeder.	1) Only operates in X,Y plane, with a Z axis. 2) Limited working volume, but easy to visualise for a 2D space. 3) Working volume is cylindrical in nature, complex to utilise. 4) Payloads can be limited if full operating speeds are required.	1 (Best)
Cartesian	1) The Cartesian style of robot can carry out fastening type operations. 2) Cartesian robots are made up from linear axis and can provide large working volumes. 3) Cartesian robots can support significant payloads, suitable for the operation of an electric screwdriver. 4) Cartesian robots have good repeatability, making them suitable for electronic assembly operations.	1) It has limited compliance in the X,Y plane. 2) Cartesian robots tend to be the slowest of the different robot types. It may not be possible to meet the takt time required in servicing the two phone lines.	2
Anthropomorphic	1) Very flexible robot, capable of working in a number of planes. (Not required in this application) 2) Can be re-tasked or have its role extended to other tasks easily.	1) Stiffness in the Z axis is limited. This is due to limited torque available in the wrist axis. 2) Complex working volume that is spherical in nature. 3) The anthropomorphic is one of the slowest robots. 4) The repeatability of the anthropomorphic robot is mid-range and may need to be examined closely for applications in electronic assembly.	3
Delta	1) The Delta robot has good repeatability required for electronic assembly.	1) The working volume of the work space is limited in the Z Axis. Challenging to accommodate screwdriver operations. 2) Payloads on the Delta robot is limited and not suitable for screwdriver operations. 3) The Delta robot doesn't have the appropriate stiffness in the Z Axis to support fastening type operations.	4

b)

i) A possible configuration for the mounted screwdriver is given below



Suggested answers for actuators, sensors are given below:

Actuators	**Operation**
Linear guide rail	To allow the screwdriver to move up and down during the fastening operation independently of the robots motion.
Pneumatic piston / Control valve	To allow the screwdriver to be lifted prior to a fastening operation and to ensure a positive pressure is applied to the screw during the self-tapping process.
Vacuum port / Control valve	To control the vacuum pick-up capability on the screwdriver.

Sensors	**Operation**
Screwdriver in the up location (Inductive – Proximity) Best (Optical – Diffused Sensor) Possible but needs to cleaned	The sensor will be used to inform the control logic of the robot controller when the screwdriver is in the up position.
Screwdriver in the down location (Inductive – Proximity) Best (Optical – Diffused Sensor) Possible but needs to cleaned	The sensor will be used to inform the control logic of the robot controller when the screwdriver is in the down position.
Vacuum sensor attached to vacuum pickup port. (Diaphragm style with threshold control) Best (Diaphragm style with switch control) Possible	The sensor will be used to inform the control logic of the robot controller that a screw has been picked up and is correctly engaged on the torque screw driver.
Screwdriver torque contactor (Internal)	The torque contactor will be used to inform the control logic of the robot controller that a screw has reached the required torque for a correctly fastened screw.

Some possible error conditions and their links to specified sensors are as follows

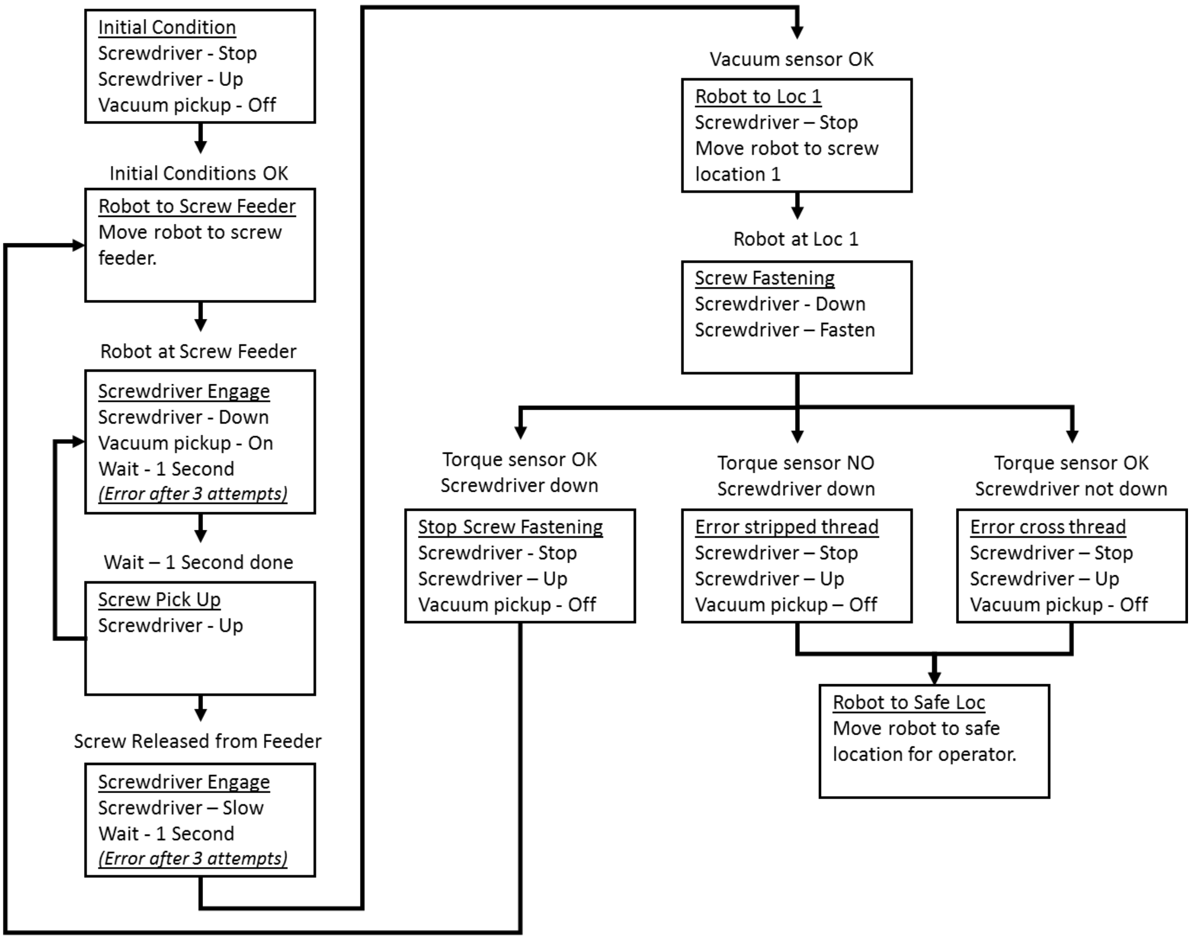
Error Condition	**Sensor States**
Stripped thread on screw	Torque sensor (No) & Screwdriver down (Yes)
Cross threaded screw	Torque sensor (Yes) & Screwdriver down (No)
Incorrect screw pick-up and/or bit engagement	Slow speed engaged & Vacuum sensor (No)
Correctly fastened screw	*Torque sensor (Yes) & Screwdriver down (YES)*

ii)

Draw a flowchart that depicts the logic required to control the operation of the screwdriver and end-effector when performing all actions required in fastening a screw.

The diagram below depicts a possible flow chart for this problem. The key items required to be evident in the flowchart are

1. Set the initial conditions of the screw driver (Up Position and Stop)
2. Move robot to a screw pick up location.
3. Pick up Screw (Sensor checks required) maybe from an external screw feeder.
4. Slow speed driver rotation, ensure screw engages on torque bit. (Sensor checks required)
5. Move robot to screw fastening location 1.
6. Fasten screw (Sensor checks required) a) Fastened, b) Stripped Thread & c) Cross Threaded
7. Repeat operation via (step 2) Question only asks for one screw!
   Good answers could show loop for multiple screws.



Question 4

(a)

Process	Description	Comments	Eco-impact
Mechanical recycling	Shred, sort, clean thermoplastics. In-factory or targeted waste streams can produce recycled polymer that can be re-used for high-grade applications.	Reduces amount of virgin polymer required to make products, e.g. closed-loop recycling of milk bottles	Significant eco-impact reduction, if processing is not too energy-intensive
	Post-consumer polymer waste stream more often results in downcycling: mixed polymers, contamination.	Limited reduction of use of virgin materials.	Possibility of some eco-impact reduction, but variable and generally low
‘Other’ mechanical recycling	Polymer used as filler or combined with other materials, e.g. for playground surfacing	Can be used for thermosets and for mixed polymers	Limited benefit
Chemical or feedstock recycling	Polymer broken down into constituent molecules	Energy intensive process, but has some robustness to impurities	High energy use means high costs; generally beneficial only for specialist polymers
Biodegradation	Composting, generically. Aerobic degradation resulting in products that are benign or beneficial as soil enhancers	Suitable only for small number of polymers. Capability of commercial composting facilities to process effectively is unclear	Unclear. The idea is good, but problematic implementation means that benefits may be limited
Burning	‘Thermal recycling’ with energy recovery	Energy from waste plants, or cement making	Beneficial when using well-controlled processes, but if uncontrolled can pollute dangerously (e.g. acid or dioxins in gases, toxic ash residues)
Landfill	Polymer included in waste stream that is placed under anaerobic conditions	Landfill space is limited; polymer waste is a potential resource so there may be missed opportunities here	Polymer is mainly inert so eco-impact is small. Uncontrolled landfill thought to be main contributor to ocean plastic.

Basic answer: Identify and briefly describe main process categories, with indication of eco-impact.
Good answer: Demonstrate understanding of all main processes and their eco-impact.
Excellent answer: Critical assessment of applicability and eco-impact of all processes.

Examiner’s comments: Some very good answers, but many lacked detail, missed some processes or were very inaccurate in parts.

(b) Recycling polymer to high-grade material is technically difficult because the polymer cannot be purified, so mechanical recycling relies on being able to *sort* and *clean* polymer waste to produce high purity material as the *input* to the recycling process. Difficulties increased by additives in polymers, use of coloured polymers, and use of mixed (often multi-layer) polymers to improve functionality (e.g. multi-layer polymer film). Costs are increased.
Handling of polymer films is difficult.
Economic benefits are at best marginal: oil prices are low so virgin polymers are relatively inexpensive and there's no margin to accommodate costs of collection, sorting, cleaning and processing. Recycled polymers command only low prices unless they are from very well-controlled waste streams: the quality has to be consistently high to get close to virgin polymer prices.
Public perceptions of plastics as 'cheap' and post-consumer polymer as 'just rubbish' can de-emphasise importance of recycling.
Basic answer: Identify some technical challenges plus economics.
Good answer: Show understanding of technical challenges and how they influence economics. Mention public perception.
Excellent answer: Show understanding of significance of technical issues of identification, sorting and cleaning; clearly identify problems.

Examiner's comments: Generally good or very good answers.

(c) Food packaging is (amongst other functions) designed to reduce food waste, primarily by (i) reducing damage whilst in the supply chain and (ii) increasing shelf life by providing mechanical or protective chemical environment (e.g. vacuum or inert atmosphere). Any discussion of its global environmental impact should note that packaging impact is small compared with food production (typically well below 10%), so assessment should therefore include some acknowledgement of the impact of food production. System boundaries might properly encompass food production, packaging production, transport, storage, end-of-life processing.
Environmental impact can be assessed using an LCA (full analysis of product function, system boundaries, inventory; gives impact assessment typically in 9 categories). Provides full data, but quality dependent on the assumptions made. The very considerable environmental cost of food production will often completely dominate the environmental cost of packaging: simplistic solutions to reducing food packaging waste tend to ignore this, so environmental impact is actually increased.
Eco-aware measures for reducing food packaging waste might include: reduction of non-functional packaging (already covered by existing legislation but difficult to enforce); reducing packaging volume (films instead of trays - negative impact on recyclability); making it easier for people to dispose of polymer waste to waste streams that can be recycled (uniform and clear national guidance across domestic and commercial waste disposal operatives); increase national capability for recycling by providing subsidies to recycling companies. More radical proposals look at reducing the range of polymers used for packaging, and this would require national/international agreement, such as using only a small number of uncoloured plastics.

Basic answer: Recognise that packaging reduces food waste, and that food waste dominates packaging-related environmental impact.
Good answer: Discussion of food packaging and its influence on food waste in a global context. Recognition of distinction and tension between packaging waste reduction and environmental impact reduction. One or more examples of measures for reducing food packaging waste that do not compromise environmental impact.
Excellent answer: Discussion showing good understanding of relationship between packaging waste and environmental impact. Two or more examples of measures for reducing food packaging waste that do not compromise environmental impact.
Examiner's comments: Most answers described LCA analysis, in greater or lesser detail, but not always with much specific reference to food packaging. Credit was given for addressing the problem of how to include impact of the function of the packaging in preventing food waste. Suggestions for reducing packaging impact were very variable, but credit was given for any sensible and well-argued proposals.

(d) Traditional polymers have essentially infinite degradation times in landfill or in ambient environments (including marine); the expectation is that biodegradable polymers should disappear in a finite time. Biodegradable polymers will degrade in aerobic conditions (though not in anaerobic conditions such as landfill), but generally require higher temperatures than available in domestic composting, and higher than for some commercial processes. Biopolymers (polymers produced from renewable bio-based resources) are not necessarily biodegradable; some fossil-fuel based polymers are biodegradable. The aim is to use for packaging biodegradable polymers that degrade at a comparable rate to food allow food-contaminated packaging to be processed with waste food. This is a low environmental impact route, but the product is not of very high value so financial considerations can be important. Identifying appropriate polymers during pre-processing is technically challenging (needs to be done e.g. by sorting on a conveyer belt in a MRF), and inclusion of non-degradable polymer in compost reduces value still further. In addition, biodegradable polymers which get into the traditional polymer mechanical recycling waste stream can cause contamination.
The environmental impact of biopolymer production is controversial and depends on system boundaries: by some metrics, biopolymers have higher impact than fossil fuel based polymers. Production is generally more expensive so remains small-scale and will never have the capacity to supply global demand
In summary: biodegradable polymers are at best only a very partial solution.
Basic answer: Description of biodegradable polymers with mention of potential advantages and some of the problems.
Good answer: Full coverage of issues.
Excellent answer: Critical discussion of a good range of positive and negative issues.

Examiner's comments: Generally well answered, showing good understanding of the issues.

Question 5

(a) Describe six supply chain risk mitigation strategies and explain unintended consequences of supply chain risk mitigation using examples. [50%]

(b) Compare and contrast the *traditional* and the *configurational* approach to supply chain risk management. [50%]

Crib:

(a) Describe four supply chain risk mitigation strategies and explain unintended consequence of supply chain risk mitigation using examples [50%]

The basic answer needs to describe the four of the following mitigations and unintended consequences of supply chain risk mitigations

Supply Chain Risk Mitigations:

- Increase Capacity
    - Build Centralised capacity for unpredictable demand;
    - Build decentralised capacity for managing supply chain disruptions due natural disaster
- Acquire redundant suppliers
    - Favour more redundant supply for high-volume products, less redundancy for low-volume product
    - Centralise redundancy for low volume products in a few flexible suppliers
- Increase Responsiveness
    - Favour cost over responsiveness for commodity products
    - Favour responsiveness over cost for short life products
- Increase inventory
    - Decentralise inventory of predictable , low value products
    - Centralise inventory of less predictable, high value products
- Increase flexibility
    - Favour cost over flexibility for predictable, low volume products
    - Favour flexibility for low-volume unpredictable products
    - Centralise flexibility in a few locations if it is expensive
- Increase Capability
    - Prefer capability over cost for high-value, high risk products.
    - Favour cost over capability for low-value commodity products
    - Centralise high capability in flexible source if possible

Unintended consequences of supply chain risk mitigations:

- Adding capacity increases cost of operation. High capacity cannot be sustained in long run when there is a perfect competition

- Increasing inventory increases cost of operation. High capacity cannot be sustained in long run when there is a perfect competition

- Having redundant suppliers increases cost of operation. High capacity cannot be sustained in long run when there is a perfect competition

Strong answer would include examples involving each mitigations and unintended risk mitigation consequences.

(b) Compare and contrast traditional approach of supply chain risk management and configurational approach of supply chain risk management. [50%]

The basic answer needs to be able to describe the two approaches and highlights the differences in the following suggestive categories:

Traditional approach of supply chain risk management:

- Identifying Supply chain risk characteristics
- Identifying risks linked to supply chain characteristics
- Evaluate risks
- Choose relevant risk mitigations
- Evaluate impact of chosen mitigation
- Plan mitigations
- Monitor risks and risks mitigation

Configuration approach of supply chain

- Mapping Supply chain : Including network structure, process flow, value and product characteristics
- Understanding event: characteristics and database
- Identifying risks: overlaying event data on SC map and identification of vulnerability led risk

- Mitigations: Change in network structure, alternative process flow, value adjustment and product redesign

Strong answer would present and discuss the differences in structured format with examples.

Examiner's Comments

This question was attempted by a very small number of students. Most students were able to describe six supply chain risk mitigation strategies. However, It is observed that majority of students struggled with the unintended consequences of risk mitigation strategies. For part (b) students could discuss traditional approach to supply chain risk management with examples and they were able to compare the two approaches. Weaker answers were those that talked in very general terms and did not go in to sufficient detail in their descriptions.

Question 6

(a) (i) The decision variables are the number of tables (x) and the number of chairs (y) to be made.

The objective function is to maximise total profit (Z). In mathematical form:

$$Maximise\ Z = 6x + 8y$$

The constraints are:

1. Wood constraint: $30x + 20y \leq 300$
2. Labour constraint: $5x + 10y \leq 110$
3. Non-negativity constraints: $x, y \geq 0$

(ii) The graphical representation of the feasible region (shaded) is shown below. The lines in the graph represent the constraints.

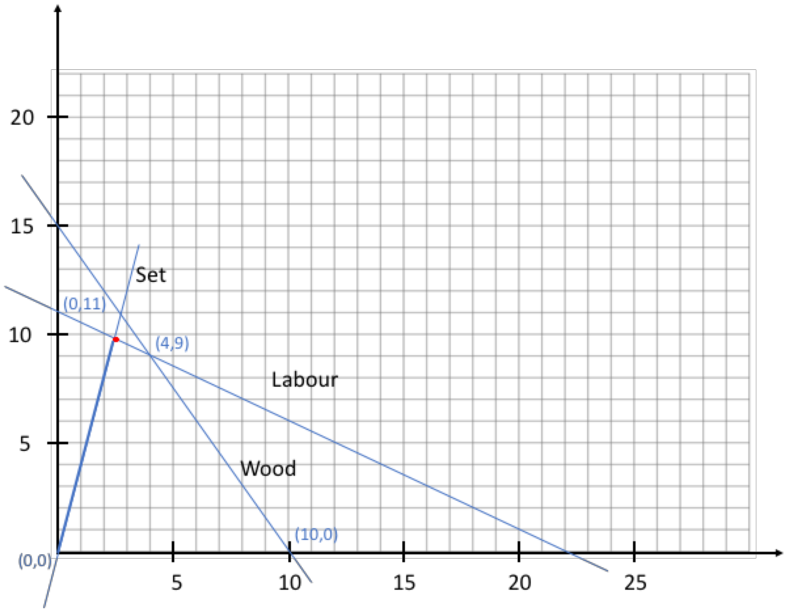
The fundamental basis of the Simplex Method is based on the fact that the optimal solution (if it exists) is a corner point feasible (CPF) solution. If a CPF solution has no adjacent CPF solutions that are better (as measured by Z), then it must be an optimal solution. The CPF solutions in this problem are (0,0), (10,0), (0,11), and (4,9). This can be found either directly by observing the graph above, or by solving for the intersections of the lines forming the constraints.

The steps within the simplex method are:
Initialisation: Choose (0,0) as the initial CPF solution to examine.
Optimality test: Conclude that (0,0) is not an optimal solution (adjacent CPF solutions are better).
Iteration: Move to a better adjacent CPF solution (0,11).
Optimality test: Conclude that (0,11) is not an optimal solution (adjacent CPF solution is better).
Iteration: Move to a better adjacent CPF solution (4,9).
Optimality test: Conclude that (4,9) is an optimal solution (adjacent CPF solutions are not better).
Hence, the optimal solution is to make 4 tables and 9 chairs, giving a total profit of £96.

(iii) If the company wants to make the furniture in sets as given in the question, we have to add a new constraint. This is given by

Set constraint: $4x - y = 0$

The revised graph will look as follows:



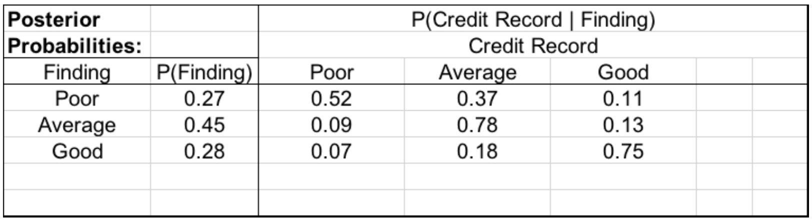
The feasible region in this case is simply the thick line-segment denoting part of the set-constraint. In this case, the optimal solution is where that line meets the labour-constraint line, which by solving the equations, we obtain as (2.444, 9.777), giving a profit of £92.88. However, only 2 tables and 8 chairs will be ready for sale at the end of each week, giving a profit of £76. At the end of the week, 0.444 tables and 0.777 chairs will be work-in-progress.

(b) (i) Assuming the credit agency is not used, the expected profit obtained from extending a credit to the new customer is given by

$$EV(credit) = 0.2 \times -1500 + 0.5 \times 1000 + 0.3 \times 2000 = £800$$

Since the profit is greater than zero, the manufacturer should extend a credit to the new customer based on current knowledge of credit-worthiness.

(ii) If the credit-rating agency is used, the revised (posterior) probabilities upon receiving the credit-rating can be found using Bayes Rule. The results of the calculation is given in the table below.



Posterior Probabilities:		P(Credit Record | Finding)				
		Credit Record				
Finding	P(Finding)	Poor	Average	Good		
Poor	0.27	0.52	0.37	0.11		
Average	0.45	0.09	0.78	0.13		
Good	0.28	0.07	0.18	0.75		

If the credit-rating given by the agency is poor, the expected profit will be -£185. If the rating is medium, the expected profit will be £911 and it will be £1571 if the rating is good. Therefore, the policy should be to reject the credit request if the rating is poor, but accept it if it is medium or good.

(iii) The expected value of receiving the credit rating is given by the difference between the expected profit the company can make if the decision is made without the credit rating (£800) and the expected profit the company can make if the decision is made with the credit-rating, given by $0.45 \times 911 + 0.28 \times 1571 = £850$. Hence, the maximum fee that must be paid to the credit agency is £50.