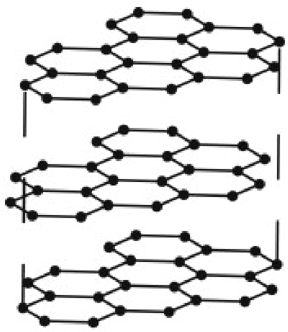
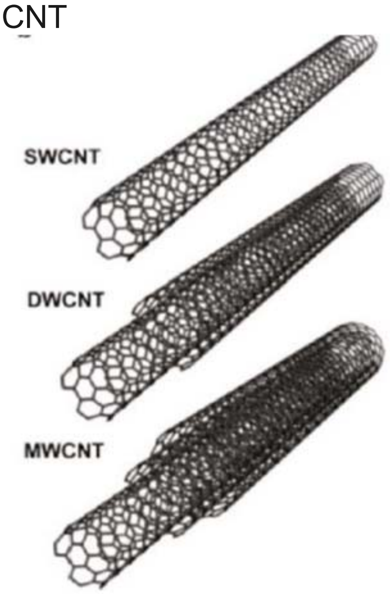
Question 1

a)
i)
Graphite and CNTs both contain arrangements of carbon atoms with covalent bonds. It is the geometric arrangement of the atoms that gives rise to their physical characteristics The carbon atoms in graphite are arranged in a two-dimensional infinite network of graphene sheets, which are stacked on top of one another to form a three-dimensional structure. This planar structure of graphite accounts for its distinct physical properties. Due to its layered structure, graphite has highly anisotropic properties. For example, its mechanical strength and thermal conductivity are high parallel to the layers, yet very low perpendicular to them. Graphite also has low hardness and a lubricating property because the molecular sheets can readily slip past one another against the van der Waals bonding.

Graphite



CNT



CNTs are cylindrical structures that consist of rolled-up sheets of single-layer carbon atoms (graphene). They can be single-walled (SWCNT) with a diameter of less than

1 nanometer (nm) or multi-walled (MWCNT), consisting of several concentrically interlinked nanotubes, with diameters reaching more than 100 nm. Their length can reach several micrometers or even millimeters. CNTs are chemically bonded with sp2 bonds, an extremely strong form of molecular interaction. This feature combined with carbon nanotubes' natural inclination to couple together via van der Waals forces, provide the opportunity to develop ultra-high strength, low-weight materials that possess highly conductive electrical and thermal properties. This makes them highly attractive for numerous applications.

Examiners Note: better answers will provide actual physical properties for CNTs:
Youngs modulus: 1 TPa
Tensile Strength: 100 GPa
Current Density: 10^9 A/cm^2
Thermal conductivity: 3500 Wm^{-1} K^{-1}

ii) CNTs are very different to carbon fibres (CFs). CFs are usually several micrometers long and have a diameter of about 200 nm. CFs have been used for decades to produce CF composites. They do not have the same lattice structure as CNTs. Instead, they consist of a combination of several forms of carbon and/or several layers of graphite, which are stacked at various angles on amorphous carbon (where atoms do not arrange themselves in ordered structures). CNFs have similar properties as CNTs, but their tensile strength and electrical/thermal performance is lower owing to their variable structure.

b)

i) Three methods for synthesising CNTs were presented in the lectures.

Arc Discharge (AD); Laser Ablation (LA) and Chemical Vapour Deposition (CVD).

AD: The main advantage of this method is its low cost with a large production of CNTs. The main disadvantage is due to poor control of the structures created.

LA: The main advantage of this technique is that it can create large amounts of SWCNTs, with high purity and quality. However, due to the laser cost and energy, this technique is the most expensive.

CVD: Compared with the two previous methods, CCVD is rather economic technique that comes in a number of forms that produce quite pure CNTs. This technique has the disadvantage of requiring several post processing steps to extract CNTs from waste products.

ii) CVD has become the standard technique for CNT synthesis.

The process steps include synthesis, purification and sorting.

Synthesis is achieved in large scale systems such as fluidised beds reactors. CVD involves the catalytic decomposition of a carbon pre-cursor (e.g., H2 and CH4, C2H2, C2H4) in carrier gas form. CO, hydrocarbons, or alcohol) on nanostructured transition metal catalyst like Co or Fe. Typical CVD temperatures vary between 500 and 1000 °C. The process is sensitive to the catalyst structuring, as well as to the reaction conditions. Nanotubes synthesised by CVD are grown on nanosecond timescales and known to be longer than those obtained by other processes. The rate of deposition of CNTs and other non-tubular carbons such as amorphous carbon and graphite depends on process/reaction conditions, the catalyst, and the precursor. During large-scale CNT self-assembly, where the CNTs are grown in a large structure, the gas- phase composition of the carbon source varies as active free radicals and intermediates at high temperature react with the precursor and among themselves.

Since the CVD process is not 100% efficient, **purification** processes are required to remove all non-CNT components such as amorphous carbon and graphite. This can be achieved by placing the CNTs into water with suitable surfactants and using high energy mixing (sonification, ball milling etc) to disperse the CNTs.

Once the surfactant encapsulated CNTs are in in solution they can be **sorted** by placing them in a centrifuge where they migrate resulting in spatial separation of CNTs (Single wall, multiwall etc). These can then be filtered, dried or stored in liquid suspension depending on the application.

c)

i) CNTs have found many applications, a number of which were presented in the lectures.

Examiners Note: here are some examples of possible answers. Candidates may offer others based on their wider knowledge.

Application of electrical properties.

CNTs have found application in **batteries.** CNTs have displayed great potential as anode materials for lithium-ion batteries (LIBs) due to their unique structural, mechanical, and electrical properties. The measured reversible lithium-ion capacities of CNT-based anodes are considerably improved compared to the conventional graphite-based anodes. Additionally, the opened structure and enriched chirality of CNTs can help to improve the capacity and electrical transport in CNT-based LIBs.

Carbon nanotube (CNT) **thin films** with thickness in the range of 1–100 nm can exhibit high electrical conductivity and high optical transparency. Compared with other potential materials to replace ITO, CNT films not only enable an easier fabrication process, but also provide a more stretchable and flexible platform with stronger mechanical strength.

CNTs have recently emerged as a promising material of **electron field emitters**. They exhibit extraordinary field emission properties because of their high electrical conductivity, high aspect ratio "needle like" shape for optimum geometrical field enhancement, and high thermal stability.

Application of mechanical properties.

The superior properties of CNTs are not limited to electrical and thermal conductivities, but also include mechanical properties, such as stiffness, toughness, and strength. These properties lead to a wealth of applications exploiting them, including **advanced composites** requiring high values of one or more of these properties.

Fibres spun of pure CNTs are undergoing rapid development, along with CNT composite fibres. Such super strong fibres will have many applications including body and vehicle armour, transmission line cables, woven fabrics and textiles.

Many corporations have already developed CNT based **air and water filtration** devices. It has been reported that these filters can not only block the smallest particles but also kill most bacteria. This is another area where CNTs have already been commercialized and products are on the market now.

ii)
Examiners note: This answer could include the following arguments, although candidates could also bring their own contributions based on their wider knowledge.

- The manufacturing techniques for CNTs are comparatively mature, with several thousand tons being produced each year, although this is much smaller than the CF market which produces 100,00t tons per year, which is even smaller than the steel market which produces some 1 billion tons per year. Manufacturers must improve production rates, efficiency levels, quality and post processing operations in order to make CNTs more widespread.
- Manufacturers must learn how to structure and organise CNTs in such a way that they retain their properties when assembled into a device. This is a significant challenge. At the moment, most carbon nanotube products are processed using traditional manufacturing techniques, such as injection moulding of CNT-polymer composites which do not give structural control over how the nanoparticles are arranged – and limit the material properties they can deliver.
- New technologies must be developed that can make devices containing well-organised nanoparticles. This should provide a dramatic improvement in their performance and open up a whole raft of new applications.
- CNTs along with many other nano-particulates are largely unexplored in terms of possible health hazards. A number of studies suggest that CNTs in sufficient quantities pose an increased health risk. Great understanding is required of the impact that CNTs have on the health and well being of people using CNT based products and the health risk associated with their disposal/reclamation.

Question 2

(a) (i) A basic answer will note that biomimetics is bio-inspired engineering or materials science. A strong answer will note more clearly that biomimetics is about studying biological phenomena in detail, specifically those that are identified as showing interesting material properties (e.g. non-wetting, high toughness, vibrant colours, etc.) that are not observed in our current engineered materials. Following this analysis, the new understanding is used to guide the development of equivalent material performances in engineered materials. An excellent answer will also note that biomimetics, while often focusing on the physical solutions, may also be seen in software solutions, e.g. genetic algorithms.

(ii) As indicated in the question, a complete answer should identify the biological inspiration for the example biomimetic material. A basic answer will note this briefly, wheras a strong answer will describe the biological solution, how the natural material achieves its properties and why this would be a useful material property to achieve in engineered products. An answer will then describe the details of the material properties of the engineered product and the details about how such properties are achieved through modifications to the materials, creation of composites, etc. Candidates are likely aware of a range of biomimetic materials and all answers will be considered. It is likely that examples described in the lectures will be presented and these include, as an example, analysis of the lotus leaf, where the surface tension balance shows that a water drop will not spread on the material. Also, the microscale and nanoscale roughness amplifies this effect further. Specifically, as the droplet is mostly in contact with air, because of the fine structures on the surface, the overall contact angle is close to 180 degrees, and so the water droplets roll down the surface. This is considered a useful property in engineered materials as it can lead to 'self-cleaning' where the rolling droplets pick up contamination and keep rolling away. We can engineer materials by structuring their surface in a similar way, either through lithography on a small area, or by laser ablation on the larger scale. Secondly, it is important to ensure the surface chemistry is also similarly hydrophobic to again have both the surface chemistry and surface structure effects combining to give a superhydrophobic behaviour.

(b) (i) The key point to convey is that biopolymers are produced from renewable natural resources, such as the waste leaves, stalks and cobs of corn/maize. These are alternative source materials but are used to produce identical materials to those from conventional, non-renewable sources. A strong answer will also note that, similar to conventional polymers, biopolymers are not necessarily biodegradable or biocompatible.

(ii) This is a broad question and the candidates may draw upon the lecture on biopolymers or indeed their additional knowledge from other modules.

Challenges in delivering the properties required. There are specific properties needed that are already delivered by conventionally-sourced polymers. It is challenging to meet these with direct replacement, for example balancing the need for good biodegradability with strength, trying to deliver the same level of transparency, flexibility, etc.

It is very complex to deal with disposal. The majority of biopolymers are not recyclable. It is likely that each new biopolymer introduced will need to be considered within the existing sorting and recycling system to ensure it does not contaminate other streams. The degradation needs to be fully understood and communicated to avoid further issues. Most biopolymers can't be composted at home and many are not suitable for standard industrial composters. If we increase the number of biopolymers without delivering a suitable method of composting then these materials will end up in landfill. Similar to the issue with food in landfill, this generates methane.

The economics of introducing biopolymers is still a challenge. This is because costs are still higher than conventional plastics. While one way forward would be to base the cost on the full life cycle of the material and its associated costs, the life cycle assessment of these materials is challenging to deliver in a way that is globally accepted.

To develop that point further, it is often challenging to identify clearly the sustainability benefits of biopolymers because often the LCAs are not considering the full system. There needs to be more understanding about the full picture and impact on emissions due to transport requirements, farming practices, soil health, biodiversity, disposal (which is often different within regions of a country).

Additional points may be discussed regarding competition of source material growth with food production, the energy sources needed during production, the need for fertiliser, pesticides, and water to support this industry. Fertiliser use has a significant impact on surrounding ecosystem, pesticides can have unintended consequences on surrounding wildlife, water is often a precious and costly resource.

A basic answer will communicate 3 barriers clearly (or 5 very briefly). A good answer will communicate 4 barriers clearly, while a strong answer will communicate 5 or more.

(c) There are a range of steps discussed throughout the lectures on chemical process engineering. Candidates may draw upon any of the content presented to them across these lectures. An example is provided below of 5 different steps. A very strong answer will note any 5 steps correctly and show a good level of understanding of each.

As it is noted in the question that the product is a specialised polymer for the medical device sector, the candidates could validly state that one step is to decide if this is going to be a batch or continuous process and offer their opinion on the considerations needed. For example, they may note that if low volumes are needed at only 1-2 sites, and the product is stable, they may create this using a batch process. They may highlight advantages such as the improved flexibility of this approach so the firm can make multiple products, or challenges such as needing to carry out quality analysis only after production. If the candidate is considering a widespread medical device manufactured in many places globally, a distributed manufacturing approach may be more suitable and a continuous process could be considered.

With either approach to manufacturing, batch or continuous, one of the first steps is to create firstly a block diagram of the process. This is a simple diagram highlighting the sequence of steps that need to happen from the input raw materials to the output product. This will be converted into an initial flow diagram where the likely unit operations and reaction engineering elements of production are included. If noting this, a strong answer would explain or give examples of what is meant by unit operations.

An important step is then to consider the full material and energy balances of the process. This is critical to understand the quantity of input materials needed and final material produced. Flows/masses in each part of the production system need to be

quantified, including separation and recycling steps, to ensure the design can be developed further. Initial equipment selection can occur based on this step.
Detailed process flowsheeting will then be carried out. At this point, each unit operation or reactor will need to be understood in more detail. There will be calculations carried out to ensure the right temperatures, pressures and flows are specified. This is carried out using simulation software and is coupled with experience.
A hazard identification stage will also need to be carried out prior to costing. This will use the process flow sheets to scrutinise the entire system and for each component identify what it needs to carry out, the possible deviations that could occur from its intended use, the potential causes of such deviations and the potential results of such an event. These will be assessed in terms of theor potential hazard and may lead to the need to re-design parts of the manufacturing system to ensure safety.

Question 3

ai)
Core to the design of the solution is the type of robot chosen. Currently two families of robot exist, collaborative and traditional robots with overlapping performance characteristics. Either family of robot can be used but the following characteristic should be considered in the design.

Solution Types (General)	Comments
Collaborative Robots (General)	Flexible operations, both manual and automated Operators can work in close proximity to the robot Speed of robot motion is limited Robot payloads are limited (Limited product range) Challenging end-effector design (finger pinching) No need for safety guards
Traditional Robots (General)	Constrained operations, typically only automated Operators can't work in same work space as the robot Speed of robot motion is high Robot payloads are higher (Greater product range) Robot can be fitted to additional axis for flexibility Safety guarding / interlock systems are mandatory

The following design makes use of a traditional robot rather than a collaborative robot, as the machine company has highlighted the need for improved cycle times and reduced operator availability. The robot and machine tools could be configured in a number of ways to facilitate different degrees of flexibility and operator accessibility. The best accessibility can be achieved by having the machine tools and the conveyor load / unload station aligned side by side with an anthropomorphic robot mounted on a linear rail / axis, servicing all three areas from above. A slightly cheaper approach would be to mount the linear axis on the ground in front of the machine tools and the conveyor load / unload station. The cheapest approach with the least flexibility can be seen below in Figure d.

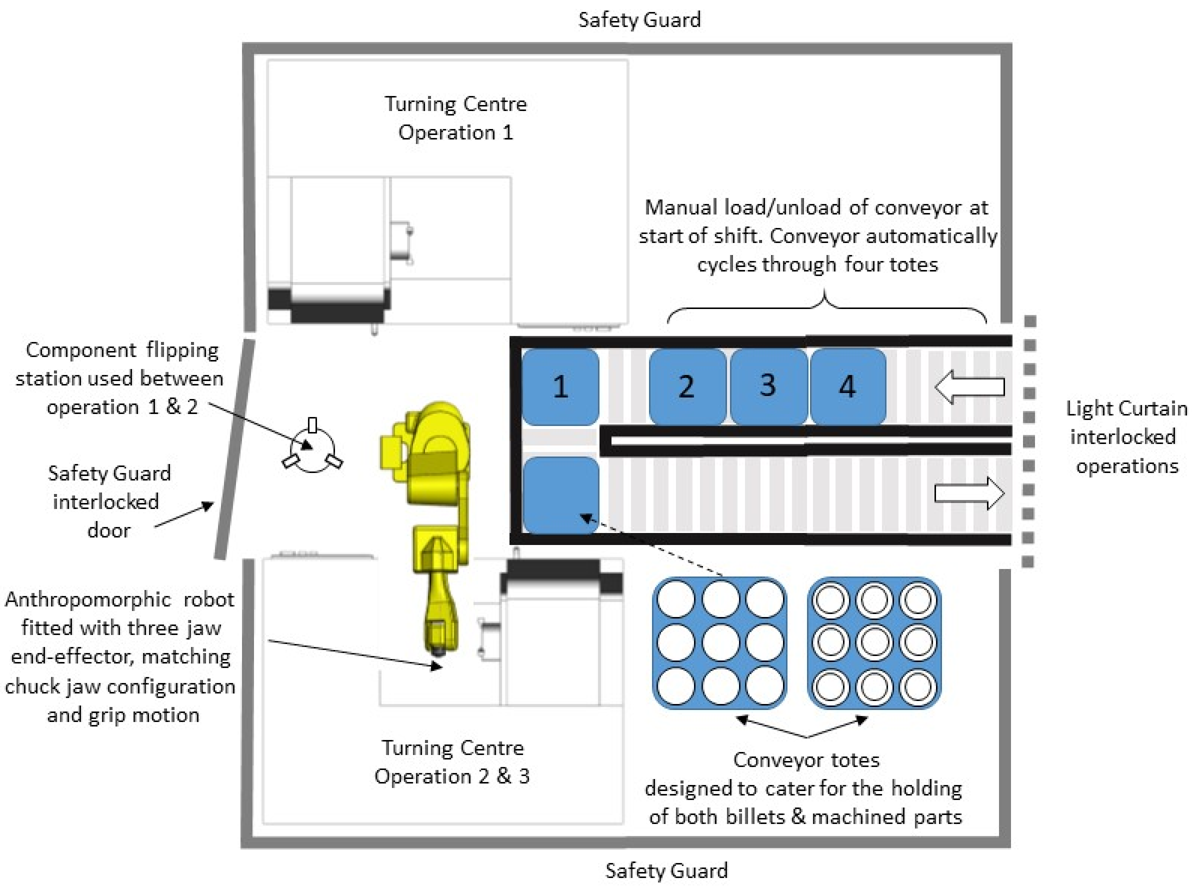


Figure d. (Automated turning centre layout)

Overall Operations	Description
1. Turning Centres	The machining of the pulley component would be split across the two turning centres. OP1 being performed on the turning centre without the Y axis and live turret. OP2 & 3 being performed on the turning centre with the Y axis and live turret.
2. Conveyors	The conveyors provide a buffer stock of totes, to service the machining operation over a four hour period. The conveyor has one docking station that can be used to locate and secure totes allowing the robot to perform load / unload operations.
3. Totes	Totes are used to locate materials and parts that are moving around the system. Carriers within the totes would be designed to allow either raw material or machined parts to be located. (9 Parts)
4. Robotic Material Handling	The robot is an anthropomorphic robot, providing enough agility to load parts in

	and out of chucks through the turning centre doors.
5. Robot end-effector (Controlled via robot progs)	The robot would be fitted with a three jaw end effector, mimicking the function and motion of the three jaw chuck on the turning centres.
6. Component flipping station	The component flipping station is required so that the part can be re-gripped by the robot in a flipped orientation between operation 1 and 2.
7. Guards, Interlocks, E-Stops and Light Curtains	This design makes use of a traditional robot and conveying system making guards, interlock and stop buttons (E-Stops) mandatory. The part load and unload from the conveyor is via a light curtain. This can be implemented to allow totes to be exchanged without the robot needing to stop.

aii)
The current production rate is limited by the machining time of the single turning centre. With OP1 + OP2 + OP3 come to 8 Mins. The machining operation can be split / balanced across the two turning centres as shown below:

Turning Centre	Operation 1	Operation 2	Operation 3
Turning Centre without Y axis and turret (New Machine)	**Capable – 4 Min**	Capable – 1 Min	
Turning Centre with Y axis and turret (Existing Machine)		**Capable – 1 Min**	**Capable – 3 Min**

In the optimum case when the two turning centres are run simultaneously, the production rate can be increased from 5 parts an hour to ~7.5 parts an hour. Therefore, in a four hour period 30 parts could be produced. The conveyor and tote system are provided to support unmanned operation. With each tote holding 9 parts, four totes will be required to cater for the period of unsupervised production.
To achieve optimum performance:

Equipment Operation	Description
1. Turning Centres	Turning centre operations would be triggered after the successful loading of materials and on the completion of a previous machining operation.
2. Conveyors	The conveyor would service totes with the following priorities. a) Release completed totes from the docking station to the output conveyor.

	b) Load next available tote into the docking station to be located and secured. c) Totes are advanced forward into available spaces.
3. Robotic material handling	To cater for any operational variations in machining times or stoppages, the robot would service the machine tools with the following priorities. a) unload turning centre OP2 & 3 to outbound tote, b) unload turning centre OP1 to flip station, c) load turning centre OP2 & 3 from flip station, d) load turning centre OP1 from inbound tote, Note the flipper station is being used to flip parts and provide buffering to ensure uptime on the OP1 turning centre.
4. Component flipping station	The flip operation would be performed once a component has been loaded and secured in the chuck and the robot is clear.

b)
The operation of the cell would be controlled / sequenced via a Programmable Logic Controller (PLC). The PLC is a rugged computer that is designed for the control of industrial applications. It has IO's and network interfaces that allow it to communicate with different pieces of equipment and a processer that allows it to perform logic tasks in a deterministic manner.
Sophisticated equipment such as robot controllers and turning centres will have their own dedicated controllers with inbuilt PLC functionality. Simpler pieces of equipment such as the tote conveyor may not be fitted with any internal controls and may require an external PLC to be integrated into sensors and actuators on the conveyor.
A typical machining cell architecture can be seen in Figure e.

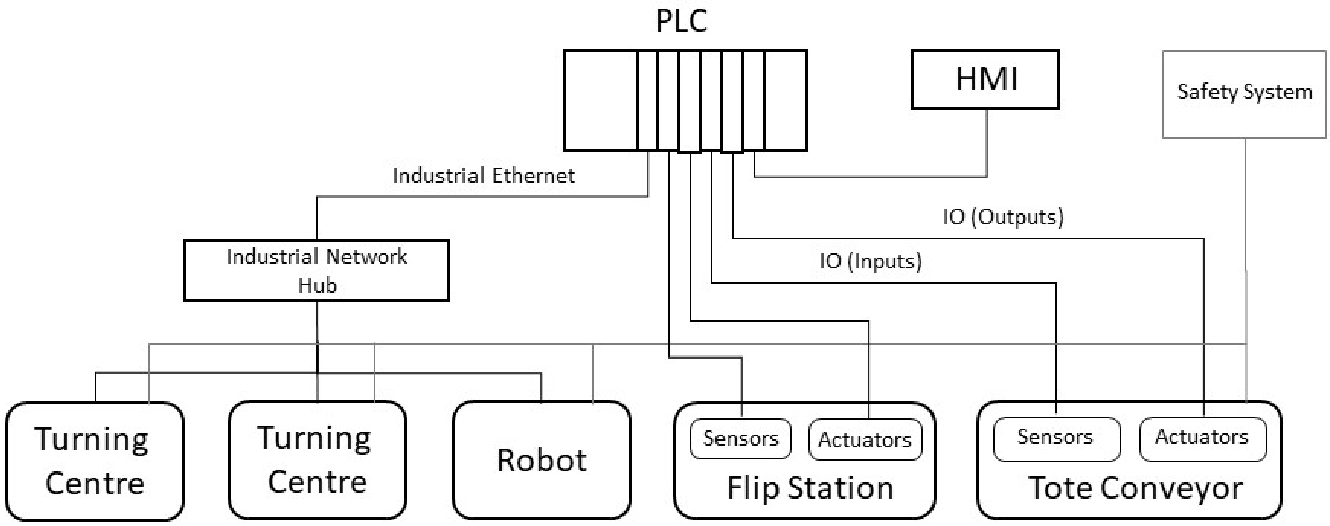


Figure e. (Machining cell control architecture)

Hardware	**Control Functions**
Turning Centres	Prog. select: Machine 1 (OP1), Machine 2 (OP1 & OP2) Prog. start / finished Auto door open / closed Chuck align, Chuck orientate, Jaws open / closed Alarm / Error Conditions
Robot	Prog. select: Load (OP1) from tote location 1-9, Unload (OP1) to flip station, Unload flip station to (OP2), Unload (OP2) to tote location 1-9. All robot programmes will end with the robot in safe home position. Prog. start / finished 3 Jaw gripper open / closed Alarm / error conditions
Flip Station	Flipper chuck open / closed, Prog. select: Flip, Un-flip Prog. start / finished Alarm / error conditions
Tote Conveyor	Enable manual load / unload function Auto advance tote into dock and tote to output rollers Locate and secure tote in dock / release tote Alarm / error conditions
PLC	Sequence of material handling, machining operations and alarm / error conditions that occur

Question 4

a) The design for the pneumatic control system on the tote diverter can be seen in Figure c.

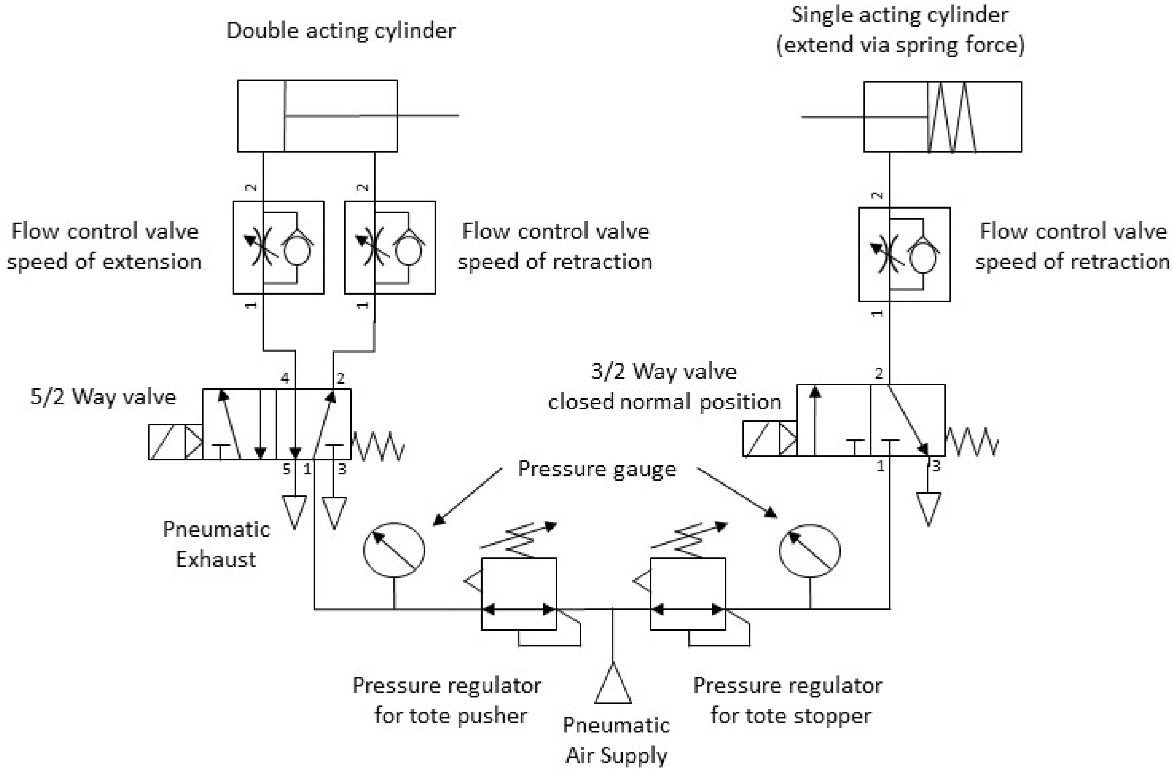


Figure c. (Pneumatic circuit for diverter control system)

Component Used	Description
Double acting cylinder (Required)	This cylinder has been used to actuate the tote pusher. This cylinder can be used to generate different forces and speeds of motion either when retracting or extending.
Single acting cylinder (Spring extended) (Required)	This cylinder has been used to actuate the tote stopper. This cylinder defaults into a sprung extended position and will do so even when pneumatic and power sources fail. (Note that the extend force is limited by the properties of the internal spring.)
Flow control valves (Required)	Flow control valves can be varied and set to control the flow of air going into a cylinder and thus its speed of operation. (Flow control is in direction 1 to 2, no flow restriction is applied in direction 2 to 1 when air exits the cylinder.) 2 flow control valves are used on the double acting cylinder to get

	independent speeds of operation when extending or retracting the tote pusher. 1 flow control valve is used on the single acting spring extending cylinder to control the speed of the tote stopper retraction.
5/2 Way valve (Required)	The 5/2 way valve has been chosen to control the double acting cylinder. It can switch both the supply and exhaust paths when operating. In its de-energised normal state, the tote pusher will be in the retracted position. (This is an electrically energised spring return valve)
3/2 Way valve (Required)	The 3/2 way valve has been chosen to control the single acting spring return cylinder. It can switch the supply or the exhaust to the single cylinder port. In its de-energised normal state, the tote stopper will be in the extended position. (This is an electrically energised spring return valve)
Pressure gauges (Optional – nice to have)	Pressure gauges are mounted after pressure regulators to allow operators to see the air pressure being use for both the tote stopper and pusher. (These will be used when setting the air pressure required.)
Pressure regulator (Optional – nice to have)	The manual pressure regulator will be used to set the maximum available air pressure that will be used to operate the tote stopper and pusher. The maximum force applied by the cylinders is a factor of the cylinder diameter and the air pressure applied.

b)
The logistics company will have to install an air compressor to allow the tote diverter to operate. In some cases where only a small demand is required, a local air compressor can be used. Most factories and industrial sites install compressed air as an infrastructural provision. A compressed air system would comprise of the following components:

<table>
<tr><th colspan="2">Equipment</th><th>Function</th><th>Criticality to the diverter</th></tr>
<tr><td>Air Filter</td><td rowspan="3">Compressor / Generator</td><td>Clean in-coming air to the compressor blocking large particles entering the compressor.</td><td>Prolong life of compressor. Remove debris that could affect the operation of the diverter.</td></tr>
<tr><td>Compressor (Pump)</td><td>Compress air to achieve the pressure required.</td><td>Provide air pressure required</td></tr>
<tr><td>Oil separator / filter</td><td>Remove any oil from the air that may have been introduced at the compressor stage.</td><td>Reduce the potential for oil vapour being exhausted into the atmosphere around the diverter. (Legislative requirement)</td></tr>
<tr><td colspan="2">Reservoir (With over pressure safety valve)</td><td>Storage of air at a volume and pressure that will accommodate changing operational demands.</td><td>Provide a steady and robust supply of compressed air for the operation of the diverter.</td></tr>
<tr><td colspan="2">Pre water trap</td><td>Removal of water particles in the air</td><td>Remove water that could corrode components within the diverter.</td></tr>
<tr><td colspan="2">Air dryer (Refrigerated)</td><td>Further reduce water content in the air, reducing the temperature of the air, causing water vapour to condense and allowing it to be separated.</td><td>Remove water that could corrode components within the diverter.</td></tr>
<tr><td colspan="2">Post water trap</td><td>Removal of water particles after the dryer</td><td>Remove water that could corrode components within the diverter.</td></tr>
</table>

At various locations in the compressed air system, isolation and or dump valves will be required. These will be used in the case of emergencies when pipes become disconnected or when service engineers need to undertake maintenance on the system.

c)

Sensor Function	Sensor Type	Sensor Operation
Tote stopper extended	Inductive barrel style sensor with 3 mm range. Single sensor unit requiring minimal wiring. Minimal maintenance with no cleaning. (Low cost, high availability)	The sensor would be secured via a bracket, allowing an inductive control dog on the stopper hardware to be seen when it is in the fully extended position.
Tote stopper retracted		The sensor would be secured via a bracket, allowing an inductive control dog on the stopper hardware to be seen when it is in the fully retracted position.
Tote pusher extended		The sensor would be secured via a bracket, allowing an inductive control dog on the pusher hardware to be seen when it is in the fully extended position.
Tote pusher retracted		The sensor would be secured via a bracket, allowing an inductive control dog on the pusher hardware to be seen when it is in the fully retracted position.
Tote located in front of tote pusher	Optical retro-reflective sensor with 1M Range. Single sensor unit requiring minimal wiring. It will require a reflector and a maintenance provision to ensure the sensor lens and reflector are kept clean.	The sensor would be mounted on the edge of the conveyor, with the reflector mounted diagonally opposite, looking across the restrained tote position. When a tote is in the restrained tote position or being pushed by the tote pusher, the beam would be broken.
Tote located over the tote stopper		The sensor would be mounted on the edge of the conveyor, with the reflector mounted opposite, looking down the length of the tote stopper on the right hand side. When a tote is over

		the right hand side of the stopper the beam would be broken. (An un-broken beam would have ensured a tote has cleared the stopper location.)

Question 5

(a)

Step 1: Calculate the mean and variance of the task durations using the formulae:

$$Mean, \quad t = \frac{t_{min} + 4t_{most-likely} + t_{max}}{6}$$

$$Variance, \quad \sigma^2 = \left(\frac{t_{max} - t_{min}}{6}\right)^2$$

Activity	Predecessors	Time estimate (days)			Mean	Variance
		Minimum	Most likely	Maximum		
A: Define the project aim and scope	-	1	3	5	**3**	0.44
B: Identify project stakeholders	-	1	2	3	2	0.11
C: Develop Process map	A, B	4	6	8	6	0.44
D: Collect and analyse data	A, B	6	8	16	**9**	2.78
E: Construct simulation model	C, D	6	7	8	**7**	0.11
F: Verify model	E	1	2	3	2	0.11
G: Validate model	E	5	7	9	**7**	0.44
H: Design and conduct experiments	F, G	4	5	6	**5**	0.11
I: Draw conclusions	H	2	3	4	**3**	0.11
J: Produce report and presentation	I	1	3	5	**3**	0.44

Step 2: Calculate the earliest and latest start/finish dates and identify those tasks without slack as the critical path activities. The critical path activities are A, D, E, G, H, I and J.

Activity	Predecessors	Mean	ES	EF	LS	LF	Slack
A: Define the project aim and scope	**-**	**3**	**0**	**3.00**	**0.00**	**3.00**	**0.00**
B: Identify project stakeholders	-	2	0	2.00	1.00	3.00	1.00
C: Develop Process map	A, B	6	3.00	9.00	6.00	12.00	3.00
D: Collect and analyse data	**A, B**	**9**	**3.00**	**12.00**	**3.00**	**12.00**	**0.00**
E: Construct simulation model	**C, D**	**7**	**12.00**	**19.00**	**12.00**	**19.00**	**0.00**
F: Verify model	E	2	19.00	21.00	24.00	26.00	5.00
G: Validate model	**E**	**7**	**19.00**	**26.00**	**19.00**	**26.00**	**0.00**
H: Design and conduct experiments	**F, G**	**5**	**26.00**	**31.00**	**26.00**	**31.00**	**0.00**
I: Draw conclusions	**H**	**3**	**31.00**	**34.00**	**31.00**	**34.00**	**0.00**
J: Produce report and presentation	**I**	**3**	**34.00**	**37.00**	**34.00**	**37.00**	**0.00**

Step 3: Calculate the mean and variance of the project duration by summing up those values of the critical path activities. Mean project duration = 37 days; Variance = 4.44 days

Step 4: Assume that the mean and variance are normally distributed (reasonable assumption for large networks)

$$Z = \frac{x - \mu}{\sigma}$$

Where μ = project mean time;
x = proposed project time;
σ = standard deviation of project time;
Z = number of standard deviations x is from the mean

This value of Z can be used to find the probability of project completion before x from the Normal Distribution tables provided with the exam (the tables give the probability of Z being less than a range of values).

If the project is not completed within 40 days, the contract specifies a penalty of £3,000 for each day of delay. The estimated daily cost to the firm including wages and expenses for this project is £1000. This means that the project needs to be completed in 42 days in order to make a profit after paying the late penalties.

The probability of project completion within 42 days can be found as follows:

$$Z = \frac{x - \mu}{\sigma} = \frac{42 - 37}{\sqrt{4.44}} = 2.37$$

From the standard normal tables, the probability for $Z < 2.37 = 0.9912$.

Therefore, there is a 99.12% chance that the company will make a profit from this project.

(b)

i. Any process (and hence the simulation model) will have inherent randomness which produces variability in processing times, arrival rates etc. This makes it difficult (or incorrect) to generate valid conclusions from the output of simulation models based on a single replication. Essentially the results (e.g., average waiting time in a particular queue) obtained after each replication would be a consequence of the random numbers (based on the input probability distributions) that the modelling software picked for that replication. If the random numbers were different, the result would also be different. Therefore, the average waiting time in a queue is simply one sample out of a large "population" of possible average waiting times. Running more replications would enable us to increase the sample size, and therefore calculate the confidence intervals of the parameter (e.g., average waiting time in a queue) we are interested in. This would help in deriving statistically significant conclusions from the model.

   For example, in the problem, the analyst might be interested in identifying the bottleneck of the manufacturing process, which is widely carried out through performance analysis of queues. Based on the results provided in Table 2, we can see that the mean of the average waiting times over five replications for the Assembly process is the highest, potentially identifying that as the bottleneck. However, we can also see that the half-width, which is the 95% confidence interval of the mean is larger than that of the Testing process. It is therefore possible that Testing could be the bottleneck, and we cannot make a confident conclusion based on five replications due to the large confidence intervals obtained. Therefore, more replications are required before making any such conclusions.

ii. The number of replications necessary can be found using the formula for calculating the half-width, i.e., 95% confidence intervals.

$$Half\ width = t_{n-1}^{1-\alpha/2}\, s/\sqrt{n}$$

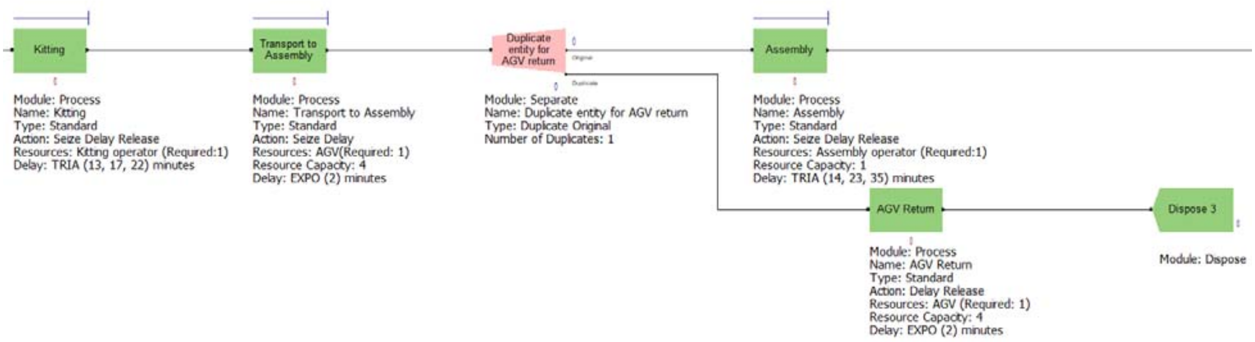
where $t_{n-1}^{1-\alpha/2}$ is the statistic of the student-t distribution (2.776 from the table provided in the exam); $\alpha = 0.05$ for 95% confidence; s is the standard deviation (provided in Table 2) and n is the number of replications.

For a half-width of 10% of the mean, we can therefore calculate the number of replications necessary:

Mean	16.30	22.92	22.56
St dev	2.67	6.85	3.79
10% Mean	1.63	2.29	2.26
Number of replications	21	69	22

From these calculations, at least 69 replications are necessary to obtain results with the necessary confidence for all the waiting times. Note that this is calculated based on the five replications. After running 69 replications, the analyst needs to check the results to ensure that the resulting confidence intervals are within 10% of the (new) means. If not, further replications may be necessary.

iii. The logic for modelling AGVs is shown in figure below.



Question 6

(a) Because we do not want the values above the mean cancelling out the values below. We also want to penalize those distances that are greater from the mean. [5 marks]
(b) We take square root to bring the metric back to the original unit of measure so it is easier to interpret.[5 marks]
(c) A parameter is a fixed value calculated from every individual in the population. [5 marks] A statistic is calculated from only some of the individuals in a population. Since statistics depend upon the representativeness of a sample, they have greater variability. [5 marks]
(d) Students will contrast the formulae for population and sample standard deviation, showing that sample standard deviation contains (N-1) whereas population standard deviation only N. [5 marks] This is because the population standard deviation is a parameter, whereas sample standard deviation is a statistic. Thus the standard deviation of the sample is greater than that of the population. [3 marks] The sample mean will always be in the sample, but there is a possibility the sample mean can even be outside the population mean. So if one takes just N, we may be underestimating the true variance of the sample. [2 marks]
The larger the value of *n* is, the closer that the population and sample standard deviations will be.
(e) Central limit theorem: When we have random samples of size n from a population with mean mu and variance S^2, sample mean X has a normal distribution with mean mu and variance S^2/n, as n becomes large, regardless of the distribution of the underlying population [5 marks]. This property allows us to perform hypothesis tests with t-stats and p-values. [5 marks]
(f) To formulate the optimization problem, we need to identify the following three elements: decision variables, the objective function and the constraints. There are six decision variables defined as the number of prospective customers to be surveyed from each population. A population is defined by a region/age group combination. [5 marks]

The objective function is equal to the total surveying cost for all six populations. This can be expressed as the sum of each decision variable multiplied by the unit surveying cost of the corresponding population. [5 marks]

There are three types of constraints [5 marks for each]. The first type contains exactly one constraint, which ensures that the sample size is 1,000. This constraint is implemented as the sum of the six decision variables, which must sum to 1,000. The second type of constraint ensures that each region as well as each age group is properly represented (as defined by the manufacturer). Therefore, we would need to model five different constraints, one for each region and one for each age group. Let us take for instance the first region. The manufacturer wants to make sure that the sample contains at least 40% from this region. This constraint is implemented as the sum of the three decision variables associated with the first region must sum to at least 400. The final set of constraints imposes that the decision variables should be defined as being integer.

(g) (i) Confusion Matrix [3 marks]

n=165	Predicted: Fail	Predicted: Healthy

Actual: Fail	20	15
Actual: Healthy	55	75

Accuracy tells us overall, how often the classifier is correct. Accuracy is calculated using (TP+TN)/total = (20+55)/165 = 0.58 [5 marks]
Recall answers the question when it's actually yes (i.e. a failure), how often does the classifier predict it? Recall is calculated using TP/actual yes = 20/(20+15) = 0.57 [5 marks]
Precision answers the question when the classifier predicts yes (i.e. a failure), how often is it correct? It is calculated using TP/predicted yes = 20/(20+55) = 0.27. [5 marks]
Based on these metrics, this is actually a pretty bad model only doing slightly better than random guess. [2 marks]
Given we have a safety critical case here, the Recall is the most important metric. Importance of Precision may depend on the action taken if failure is predicted, and its cost to the model owner. [5 marks]
(ii) The failure rate of 1% would mean that the dataset is imbalanced, i.e. it is intrinsically harder for the classifier to predict failures as there is less data available for these cases [10 marks]. In our current sample we have a failure rate of 0.21 (whereas the real life rate is known to be 35%) so the current model would be unsuitable for use in a 1% case [10 marks]. Students may comment on how to address data imbalance, in which case they receive extra marks.