METIIA Paper 2

Section A

Question 1

a) Describe the key assumptions and limitations of Merchant's cutting model when applied to machining processes. Discuss how these assumptions influence the accuracy of the predicted cutting forces and shear plane angle.

[10%]

b)

(i) Draw the Merchant force diagram for a machining process. Label all forces and angles clearly and describe their physical significance.

[15%]

(ii) Discuss the effect of increasing the rake angle (α) on the cutting forces, shear angle, and energy efficiency of the machining process.

[10%]

(iii) Show that

$$\tan\phi = \frac{r\cos\alpha}{1 - r\sin\alpha}$$

Where *(r)* is the cutting ratio, (α) is the rake angle, and (ϕ) is the shear angle.

[20%]

c) A manufacturing process involves machining a workpiece using the following conditions.

- Cutting velocity (V): 120 m/min
- Undeformed chip thickness (t_1): 0.15 mm
- Deformed chip thickness (t_2): 0.3 mm
- Cutting force (F_c): 1500 N
- Thrust force (F_t): 600 N
- Rake angle (α): 12^0

(i) Calculate the percentage of the total power that is dissipated in the shear plane. Comment on your answer.

[25%]

(ii) Calculate the shear plane angle (ϕ) using Merchant’s equation.

$$\emptyset = 45° + \frac{\alpha}{2} + \frac{\beta}{2}$$

How does this result compare with previous result using the chip ratio method? Comment on any discrepancies.

[20%]

Question 1 Crib

a) **Key Assumptions of Merchant's Model**:

1. The cutting process is two-dimensional and orthogonal.
2. The chip is a rigid body that slides over the rake face without deformation.
3. Friction at the tool-chip interface is constant and can be represented by a single friction angle (β).
4. The shear plane is a single, well-defined plane, and the material undergoes shear deformation along it.
5. The workpiece material is isotropic and homogeneous.

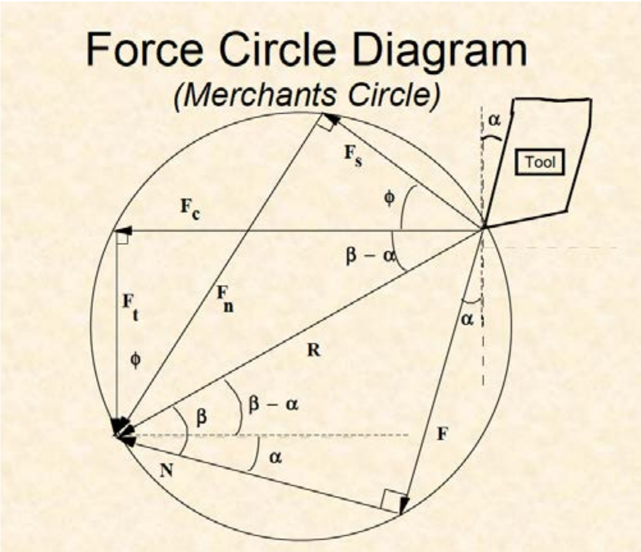
Influence of Assumptions:

- The assumption of a single shear plane neglects complex material flow and secondary deformation zones, leading to inaccuracies in force predictions.
- The constant friction assumption simplifies calculations but does not capture variations in friction due to temperature or material properties.
- The model assumes idealized tool geometry, which may not account for tool wear or complex rake face designs.

[Assumptions: 5 marks, Influence: 5 marks]

b)

i) The Merchant force diagram for this process is given as



The Merchant force diagram represents the relationships among forces acting during the cutting process. The forces include:

- **Cutting force (F_c)**: The force acting parallel to the cutting direction.
- **Thrust force (F_t)**: The force perpendicular to the cutting direction.
- **Shear force (F_s)**: The force acting along the shear plane, responsible for material removal.
- **Normal force on the shear plane (F_n)**: The force perpendicular to the shear plane.
- **Resultant force (R)**: The vector sum of all forces.
- **Friction force (F)**: Friction force acting along the tool-chip interface
- **Friction angle (β)**: Angle between the Resultant force and the normal to the Friction force.

- **Rake angle (α)**: Angle between the surface normal and tool rake face.
- **Shear angle (ϕ)**: Angle between the machined surface and the shear plane.

[Diagram: 10 marks, Explanation: 5 marks]

ii)

S**hear Angle (ϕ)**:

- An increase in rake angle (α) increases ϕ, as seen from Merchant's equation. A larger shear angle leads to thinner shear zones and reduces cutting resistance.

Cutting and Thrust Forces:

- Increasing α decreases the frictional component along the rake face, reducing cutting force (Fc) and thrust force (Ft).

Energy Efficiency:

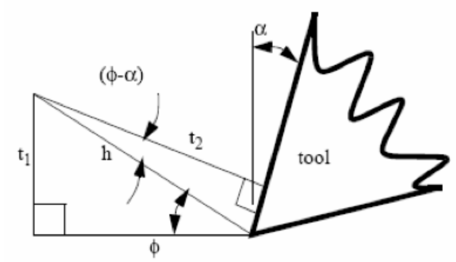
- A larger rake angle reduces energy losses due to friction, increasing the energy efficiency of the machining process.

Practical Limitations:

- Excessive rake angle can weaken the tool edge, making it susceptible to chipping or failure.

[Qualitative discussion: 10 marks]

iii)



$t_1 = h\sin\phi$ and $t_2 = h\cos(\phi - \alpha)$

Using the definition for the cutting ratio, r = t_1/t_2

$$r = \frac{h\sin\phi}{h\cos(\phi-\alpha)} = \frac{\sin\phi}{\cos\phi\cos\alpha+\sin\phi\sin\alpha}$$

$$r\cos\phi\cos\alpha + r\sin\phi\sin\alpha = \sin\phi$$

$$\frac{r\cos\phi\cos\alpha}{\sin\phi} + \frac{r\sin\phi\sin\alpha}{\sin\phi} = 1$$

$$\frac{r\cos\alpha}{\tan\phi} + r\sin\alpha = 1$$

therefore

$$\boldsymbol{\tan\phi = \frac{r\cos\alpha}{1 - r\sin\alpha}}$$

where r is the cutting ratio, α is the rake angle, and ϕ is the shear angle.

c)

(i)

The chip ratio (r) is given by:

$$r = \frac{t_1}{t_2}$$

Substituting:

$$r = \frac{0.15}{0.3} = 0.5$$

Using the formula for shear plane angle:

$$\phi = \arctan\left(\frac{r \cdot \cos\alpha}{1 - r \cdot \sin\alpha}\right)$$

Substituting values ($\cos 12^\circ = 0.9781$, $\sin 12^\circ = 0.2079$):

$$\phi = \arctan\left(\frac{0.5 \cdot 0.9781}{1 - 0.5 \cdot 0.2079}\right)$$

$$\phi = \arctan\left(\frac{0.48905}{0.89605}\right) = \arctan(0.5457)$$

$$\phi = 28.56^\circ$$

The shear force is given by:

$$F_s = F_c \cos\phi - F_t \sin\phi$$

Substitute $\cos 28.56^\circ = 0.8779$ and $\sin 28.56^\circ = 0.479$:

$$F_s = 1500 \cdot 0.8779 - 600 \cdot 0.479$$

$$F_s = 1316.85 - 287.4 = 1029.45\,\text{N}$$

The shear velocity is given by:

$$V_s = V \cdot \cos\phi$$

Substitute $\cos 28.56^\circ = 0.8779$:

$$V_s = 2 \cdot 0.8779 = 1.7558\,\mathrm{m/s}$$

Shear power (P_s) is: :

$$P_s = F_s \cdot V_s$$

Substitute $F_s = 1029.45\,\mathrm{N}$ and $V_s = 1.7558\,\mathrm{m/s}$:

$$P_s = 1029.45 \cdot 1.7558 = 1806.7\,\mathrm{W}$$

The total power is:

$$P = F_c \cdot V$$

Substitute $F_c = 1500\,\mathrm{N}$ and $V = 2\,\mathrm{m/s}$:

$$P = 1500 \cdot 2 = 3000\,\mathrm{W}$$

The power of power dissipated in the shear plane is:

$$\text{Percentage} = \frac{P_s}{P} \cdot 100$$

Substitute $P_s = 1806.7\,\mathrm{W}$ and $P = 3000\,\mathrm{W}$:

$$\text{Percentage} = \frac{1806.7}{3000} \cdot 100 = 60.22\%$$

Comment:
Approximately **60.22%** of the total power is dissipated in the shear plane. The remaining energy (39.78%) is dissipated as heat and friction at the tool-chip interface, emphasising the role of friction in energy loss and tool wear.

[Correct calculations 15 marks and comment 5 marks]

(ii)

Merchant's Equation:

$$\phi = 45^\circ + \frac{\alpha}{2} - \frac{\beta}{2}$$

The friction angle (β) is:

$$\tan\beta = \frac{F_t}{F_c} = \frac{600}{1500} = 0.4$$

$$\beta = \arctan(0.4) = 21.8^\circ$$

Now substituting:

$$\phi = 45^\circ + \frac{12^\circ}{2} - \frac{21.8^\circ}{2}$$

$$\phi = 45^\circ + 6^\circ - 10.9^\circ = 40.1^\circ$$

The two methods give different values (28.56^0 vs. 40.1^0). The discrepancy arises due to the assumptions inherent in the chip ratio method, such as neglecting frictional effects, whereas Merchant's equation accounts for friction.

[Correct calculations: 10 marks, Discrepancy discussion: 5 marks]

Question 2

a)

(i) Briefly explain how a manufacturing company can apply *Statistical Process Control* (SPC) techniques to determine the performance of a turning operation and the benefits it is likely to achieve.

[10%]

(ii) Provide details of the key stages in applying SPC techniques for such an operation.

[20%]

b) A manufacturing company uses a CNC machine tool to produce precision shafts with a target diameter of *50.00 mm*. The following information applies:

Cutting Tool Life:

- The cutting tool has a life of *50 parts* under the current machining conditions. Tool wear causes dimensional variation over time.

Process Monitoring:

- Sample size (n): *5 parts* per sampling interval.
- The process is monitored every *10 parts*.

Process Capability:

- The tolerances for the shaft diameter: 50.00 ± 0.10 *mm*.
- Historical process mean: (μ) =*50.01 mm*.
- Standard deviation: (σ) = *0.03 mm*.

The data presented in Table. 1 was collected over 10 samples, 50 parts.

Table. 1

Sample No.	$\bar{X}$ (mm)	R (mm)
1	50.02	0.06
2	50.03	0.05
3	50.01	0.07
4	50.02	0.08
5	50.00	0.06
6	50.01	0.05
7	50.04	0.09
8	50.03	0.04
9	50.02	0.06
10	50.01	0.07

(i) Plot the $\bar{\mathbf{X}}$ and **R** control charts for this data. Control chart factors are given in Table 2. Comment on your answer.

[25%]

(ii) Calculate the process capability indices Cp and Cpk. Interpret the results and decide whether the process is capable of meeting the specifications.

[25%]

(iii) The process engineer is considering replacing the cutting tool after 40 parts instead of the current 50 parts. Replacing the tool reduces the standard deviation (σ) to 0.02 mm. Tool change increases downtime, leading to a cost increase of 10% per unit. Should the company adopt the new tool replacement strategy? Justify your answer based on both machining performance and cost considerations.

[20%]

Table. 2

Sample size n	Mean Factor A_2	Upper Range D_4	Lower Range D_3
2	1.880	3.268	0
3	1.023	2.574	0
4	0.729	2.282	0
5	0.577	2.115	0
6	0.483	2.004	0
7	0.419	1.924	0.076
8	0.373	1.864	0.136
9	0.337	1.816	0.184
10	0.308	1.777	0.223

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Question 2 Crib

2 a)

(i) Statistical Process Control (SPC) is a data-driven methodology used to monitor, control, and improve manufacturing processes. A manufacturing company can apply SPC to evaluate and ensure the reliability of machining operations by systematically analysing process variations, identifying deviations, and making informed decisions.

Benefits:

Early Detection of Issues:

- SPC identifies deviations in machining operations before defects occur, enabling proactive adjustments.

Improved Quality:

- By minimising variability, SPC ensures consistent product quality and reduces rework or scrap.

Enhanced Efficiency:

- SPC helps optimise machining parameters, reducing cycle times and improving throughput.

Cost Savings:

- Early intervention reduces downtime, tool replacement costs, and waste.

Data-Driven Decision Making:

- SPC provides quantifiable metrics to evaluate process improvements and justify investments in new tools or equipment.

[Definition 2 marks: benefits 8 marks]

(ii)

Stage-1 Identify Key Process Parameters

- Determine the critical characteristics of the machining operation that affect product quality (e.g., part dimensions, surface finish, tool wear).
- Example parameters for a turning operation might include:
  - Workpiece diameter.
  - Cutting force.
  - Surface roughness.

Stage-2 Define Specification Limits and Process Capability

- Establish engineering specifications, such as upper and lower specification limits (USL and LSL).
- Analyse historical process data to determine the process mean (μ) and standard deviation (σ).
- Use capability indices (Cp and Cpk) to assess whether the process is capable of consistently producing parts within specifications.

Stage-3 Collect Process Data

- Gather real-time data during machining using automated sensors or manual measurements.
- For instance, measure the diameter of machined parts every n^{th} piece or at regular intervals.

Stage-4 Use Control Charts to Monitor the Process
SPC involves creating control charts to track process stability and detect variations. The most commonly used charts are:

- **$\bar{X}$ and R Charts**:
    - **$\bar{X}$** chart monitors the process mean.
    - **R** chart monitors the variability of the process.
- **Individual (I) and Moving Range (MR) Charts**:
    - Useful for processes with a single measurement per sampling interval.

Applying Control Charts:

1. Calculate control limits using: UCL= $\bar{X}$ +A2·R_{avg}, LCL= $\bar{X}$ −A2·R_{avg}, where $\bar{X}$ is the average of sample means, and R_{avg} is the average of sample ranges.
2. Plot real-time data points on the control chart.
3. Identify trends, shifts, or points outside control limits.

Stage-5 Analyse Sources of Variation

- **Common Causes**: Natural variability inherent in the machining process (e.g., material properties, environmental factors).
- **Special Causes**: Unusual variations due to specific issues (e.g., tool wear, machine misalignment, operator error).
- SPC helps distinguish between these causes by analysing control charts.
-

Stage-6 Implement Corrective Actions
When a process goes out of control, corrective actions can be taken based on SPC findings:

- Adjust cutting parameters (e.g., feed rate, cutting speed).
- Replace or recondition worn tools.
- Recalibrate or repair machine components.
- Train operators to reduce human errors.

<u>Better answers may extend the discussion by Evaluating Process Reliability</u>
Assess Process Stability

- A stable process has no points outside control limits and no non-random patterns in the control chart.
- Stability indicates that the machining operation is predictable and reliable.

Evaluate Process Capability

- Calculate process capability indices (C_p and C_{pk}) to determine if the process can meet customer specifications.
- A C_p or C_{pk} value greater than 1.33 is typically considered capable for most manufacturing processes.

Predict Process Performance

- Use SPC to predict defect rates and reliability metrics such as yield or parts-per-million (PPM) defects.

Monitor Long-Term Trends

- SPC tracks long-term process performance, providing insights into wear patterns, machine behaviour, and the need for preventive maintenance.

[Stages – 15 marks : Evaluation 5 marks] b)

(i)

Step 1: Calculate Control Limits for $\bar{X}$ and R Charts

- **Control Limits for R Chart**:
  Using $D_3 = 0$, $D_4 = 2.114$, and the average range (R_{avg}):

$$R_{\text{avg}} = \frac{\sum R}{n} = \frac{0.06 + 0.05 + 0.07 + 0.08 + 0.06 + 0.05 + 0.09 + 0.04 + 0.06 + 0.07}{10} = \frac{0.63}{10} = 0.063$$

$$\text{UCL}_R = D_4 \cdot R_{\text{avg}} = 2.114 \cdot 0.063 = 0.133$$

$$\text{LCL}_R = D_3 \cdot R_{\text{avg}} = 0 \cdot 0.063 = 0$$

- **Control Limits for $\bar{X}$ Chart**:
  Using $A_2 = 0.577$:

$$\text{UCL}_{\bar{X}} = \bar{\bar{X}} + A_2 \cdot R_{\text{avg}}$$

$$\text{LCL}_{\bar{X}} = \bar{\bar{X}} - A_2 \cdot R_{\text{avg}}$$

First, calculate $\bar{\bar{X}}$:

$$\bar{\bar{X}} = \frac{\sum \bar{X}}{n} = \frac{50.02 + 50.03 + 50.01 + 50.02 + 50.00 + 50.01 + 50.04 + 50.03 + 50.02 + 50.01}{10} = \frac{500.19}{10} = 50.019$$

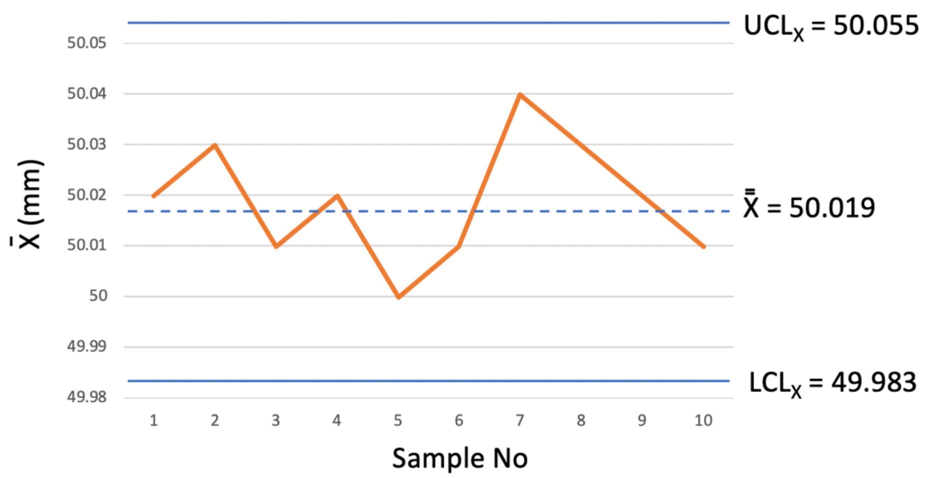
Substitute:

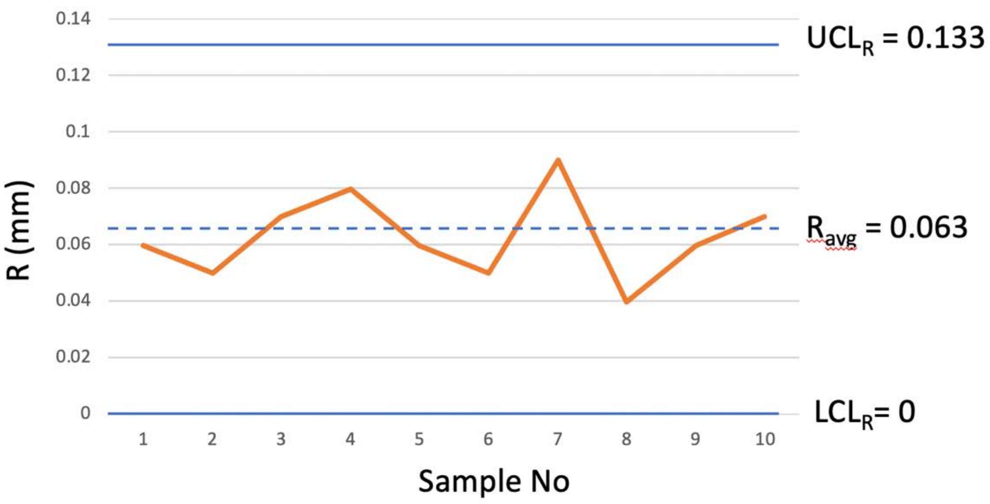
$$\text{UCL}_{\bar{X}} = 50.019 + (0.577 \cdot 0.063) = 50.019 + 0.036 = 50.055$$

$$\text{LCL}_{\bar{X}} = 50.019 - (0.577 \cdot 0.063) = 50.019 - 0.036 = 49.983$$

Step 2: Plot $\bar{X}$ and R Charts

- **Data for $\bar{X}$ Chart**:
  - Control limits: $\text{UCL}_{\bar{X}} = 50.055$, $\text{LCL}_{\bar{X}} = 49.983$, centerline $\bar{\bar{X}} = 50.019$.
- **Data for R Chart**:
  - Control limits: $\text{UCL}_R = 0.133$, $\text{LCL}_R = 0$, centerline $R_{\text{avg}} = 0.063$.





Evaluation

- **R Chart**:
  - All sample R values fall within the control limits (between 0 and 0.133), indicating that variability is in control.
- **X-bar Chart**:
  - All sample values fall within the control limits (between 49.983 and 50.055), indicating that the process mean is in control.

[Calculations and Charts – 20 marks: Evaluation 5 marks]

(ii)

Step 1: Calculate C_p

$$C_p = \frac{\text{USL} - \text{LSL}}{6\sigma}$$

$$C_p = \frac{50.10 - 49.90}{6 \cdot 0.03} = \frac{0.20}{0.18} = 1.11$$

Step 2: Calculate C_{pk}

$$C_{pk} = \min\left(\frac{\text{USL} - \mu}{3\sigma}, \frac{\mu - \text{LSL}}{3\sigma}\right)$$

Substitute $\mu = 50.01, \sigma = 0.03$:

$$C_{pk} = \min\left(\frac{50.10 - 50.01}{3 \cdot 0.03}, \frac{50.01 - 49.90}{3 \cdot 0.03}\right)$$

$$C_{pk} = \min\left(\frac{0.09}{0.09}, \frac{0.11}{0.09}\right) = \min(1.00, 1.22) = 1.00$$

Step 3: Interpret Results

- $C_p = 1.11$: The process has good potential capability.
- $C_{pk} = 1.00$: The process is slightly off-center but capable of meeting specifications.

[Calculations – 20 marks: Interpretation 5 marks]

(iii)

Step 1: Recalculate C_p and C_{pk} with $\sigma = 0.02$

- **Recalculate C_p:**

$$C_p = \frac{\text{USL} - \text{LSL}}{6\sigma}$$

$$C_p = \frac{50.10 - 49.90}{6 \cdot 0.02} = \frac{0.20}{0.12} = 1.67$$

- **Recalculate C_{pk}:**

$$C_{pk} = \min\left(\frac{\text{USL} - \mu}{3\sigma}, \frac{\mu - \text{LSL}}{3\sigma}\right)$$

$$C_{pk} = \min\left(\frac{50.10 - 50.01}{3 \cdot 0.02}, \frac{50.01 - 49.90}{3 \cdot 0.02}\right)$$

$$C_{pk} = \min\left(\frac{0.09}{0.06}, \frac{0.11}{0.06}\right) = \min(1.50, 1.83) = 1.50$$

Improved Capability:

- Replacing the tool earlier improves C_p from 1.11 to 1.67 and C_{pk} from 1.00 to 1.50, indicating better machining accuracy and reduced variability.

Cost Consideration:

- The 10% increase in cost per unit must be evaluated against the improved quality and reduced risk of defects. If the reduced variability leads to fewer rejects or rework, the additional cost could be justified.

Recommendation:

- Adopt the new tool replacement strategy if the improved capability significantly enhances product quality or reduces defect costs.

[Calculations – 15 marks: Analysis 5 marks]

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SECTION B

Question 3

CRIB

a)

i) Explain what is represented by the finite state model of an operation and how this can be used in automation solutions. [10%]

From the lecture slides:
A finite state model represents the behaviour of a system in terms of the different states that the system can be in, as well as the transitions that trigger movement between the different states.

ii) What planning steps are required before a state machine for a production operation can be developed? [10%]

From the lecture slides:

1. Determine key processing steps
2. Determine resources/equipment required
3. For each resource specify:
   - Triggers [control inputs]
   - Operations
   - Pre requisites
   - Constraints
4. Identify allowable states for each resource
5. Using key processing steps (1) and allowable state (5)
   - Identify single or joint states required for the process
   - develop state model for required operations

b) Consider a machine that forms torsion springs – coils with straight "legs" at the ends – as depicted in Figure 1 (a). A schematic, side-on view of this machine is shown in Figure 1 (b). The machine has three motor-driven mechanisms:

- Feeder: A rotating wheel that pushes a strand of wire through the machine.
- Coiler: A mechanism that extends towards the wire (as shown in Figure 1 (c)), forming the wire pushing against it into a coil.
- Cutter: A mechanism that extends towards the wire (as shown in Figure 1 (d)), cutting the wire to release the formed spring.

The machine is fitted with three sensors, which detect the length of the front leg, the length of the coil and the length of the back leg, respectively. The inputs from these sensors, as well as the inputs from the sensors and outputs to the actuators of the three mechanisms, are defined in Table 1. Assume that the Feeder is off and both the Coiler and Cutter mechanisms are in the retracted position prior to the start button being pressed. Once the start button is pressed, the intended operation of the machine can be described as follows:

- The Feeder switches on to drive the strand of wire through the machine.
- When the specified length of the front leg is detected by the sensor, the Coiler should extend towards the wire while the Feeder remains on.

- When the specified length of the coil is detected, the Feeder should stop and the Coiler should retract.
- The Feeder should drive the wire again until the specified length of the back leg is detected, at which time it should stop.
- The Cutter should then extend to cut the wire and retract.
- The sequence repeats.

i) Determine the possible states of each of the three mechanisms and identify the allowable composite states for the machine. [20%]

First determine the possible states of each mechanism:

Mechanism	*State description*	*Variable*
Feeder	*Feeder is ON*	*B1*
	Feeder is OFF	$\overline{B1}$
Coiler	*Coiler is in the retracted position*	*B2*
	Coiler is in the extended position	*B3*
	Coiler is ON and retracting	*B4*
	Coiler is ON and extending	*B5*
Cutter	*Cutter is in the retracted position*	*B6*
	Cutter is in the extended position	*B7*
	Cutter is ON and retracting	*B8*
	Cutter is ON and extending	*B9*

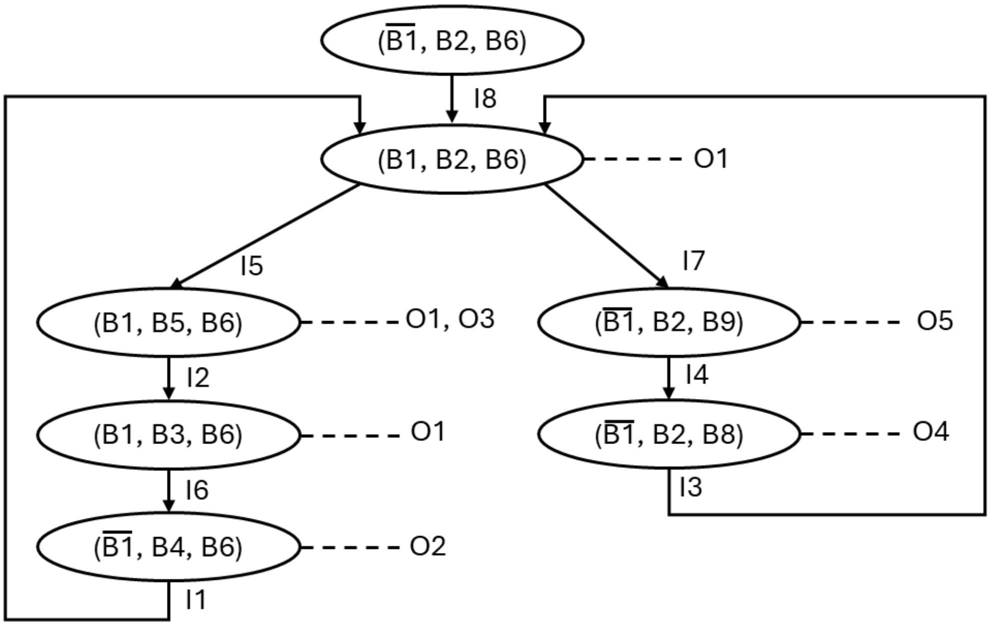
By interpreting the description of the intended operation of the machine, the following composite states would be allowable:

Operation	***Allowable composite state***
Assume that the Feeder is off and both the Coiler and Cutter mechanisms are in the retracted position prior to the start button being pressed.	($\overline{B1}$, *B2, B6)*
The Feeder switches on to drive the strand of wire through the machine	*(B1, B2, B6)*
When the specified length of the front leg is detected by the sensor, the Coiler should extend towards the wire while the Feeder remains on.	*(B1, B5, B6)*
	(B1, B3, B6)
When the specified length of the coil is detected, the Feeder should stop and the Coiler should retract.	($\overline{B1}$, *B4, B6)*
The Feeder should drive the wire again until the specified length of the back leg is detected, at which time it should stop.	*(B1, B2, B6)*
	($\overline{B1}$, *B2, B6)*
The Cutter should then extend to cut the wire and retract.	($\overline{B1}$, *B2, B9)*
	($\overline{B1}$, *B2, B7)*
	($\overline{B1}$, *B2, B8)*

(2)(4)*(4) = 32 composite states possible – more comprehensive check:*

Composite state	***Allowable?***	***Description***
(B1, B2, B6)	*Yes*	*True for front and back leg forming phases.*
(B1, B3, B6)	*Yes*	*True for coil forming phase.*
(B1, B4, B6)	*No*	*Feeder must be stopped during Coiler retracting.*
(B1, B5, B6)	*Yes*	*True for coil forming phase.*
(B1, B2, B7)	*No*	*Feeder must be stopped during cutting operation.*
(B1, B2, B8)	*No*	
(B1, B2, B9)	*No*	
(B1, B3, B7)	*No*	
(B1, B3, B8)	*No*	
(B1, B3, B9)	*No*	
… (5 states)	*No*	
(B1, B5, B9)	*No*	
($\overline{B1}$, B2, B6)	*Yes*	*Machine IDLE/OFF state (requires the model to include an ON/START input)*
($\overline{B1}$, B3, B6)	*No*	*Feeder must remain on during Coiler extension.*
($\overline{B1}$, B4, B6)	*Yes*	*Feeder must be off during Coiler retraction*
($\overline{B1}$, B5, B6)	*No*	*Feeder must remain on during Coiler extension.*
($\overline{B1}$, B2, B7)	*Yes*	*Feeder must be off and Coiler retracted during Cutter extension.*
($\overline{B1}$, B2, B8)	*Yes*	
($\overline{B1}$, B2, B9)	*Yes*	
($\overline{B1}$, B3, B7)	*No*	*Coiler must be retracted during Cutter extension.*
($\overline{B1}$, B3, B8)	*No*	
($\overline{B1}$, B3, B9)	*No*	
… (5 states)	*No*	
($\overline{B1}$, B5, B9)	*No*	

ii) Construct a finite state model of the machine. Indicate all state variables, inputs, outputs and state transition requirements. State all assumptions and justify the model that you propose. [40%]



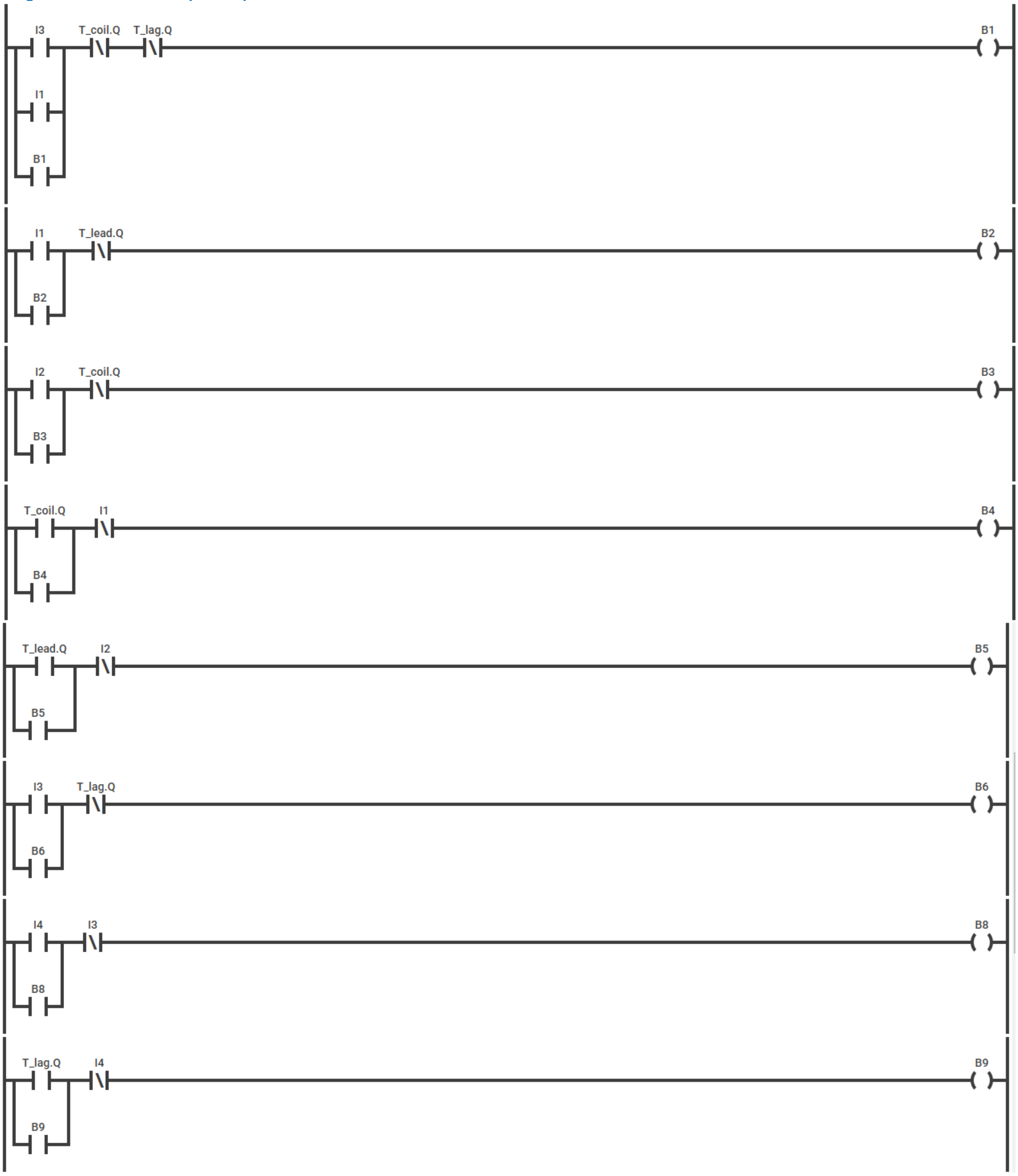
iii) The timing of the machine's operations is found to be highly repeatable. As such, instead of the three sensors that detect the length of the spring coil and legs, the torsion spring forming machine could be designed based on timers in a PLC-based control program. Explain how the replacement of the sensors with timers would be reflected in the finite state model constructed in (ii). [5%]

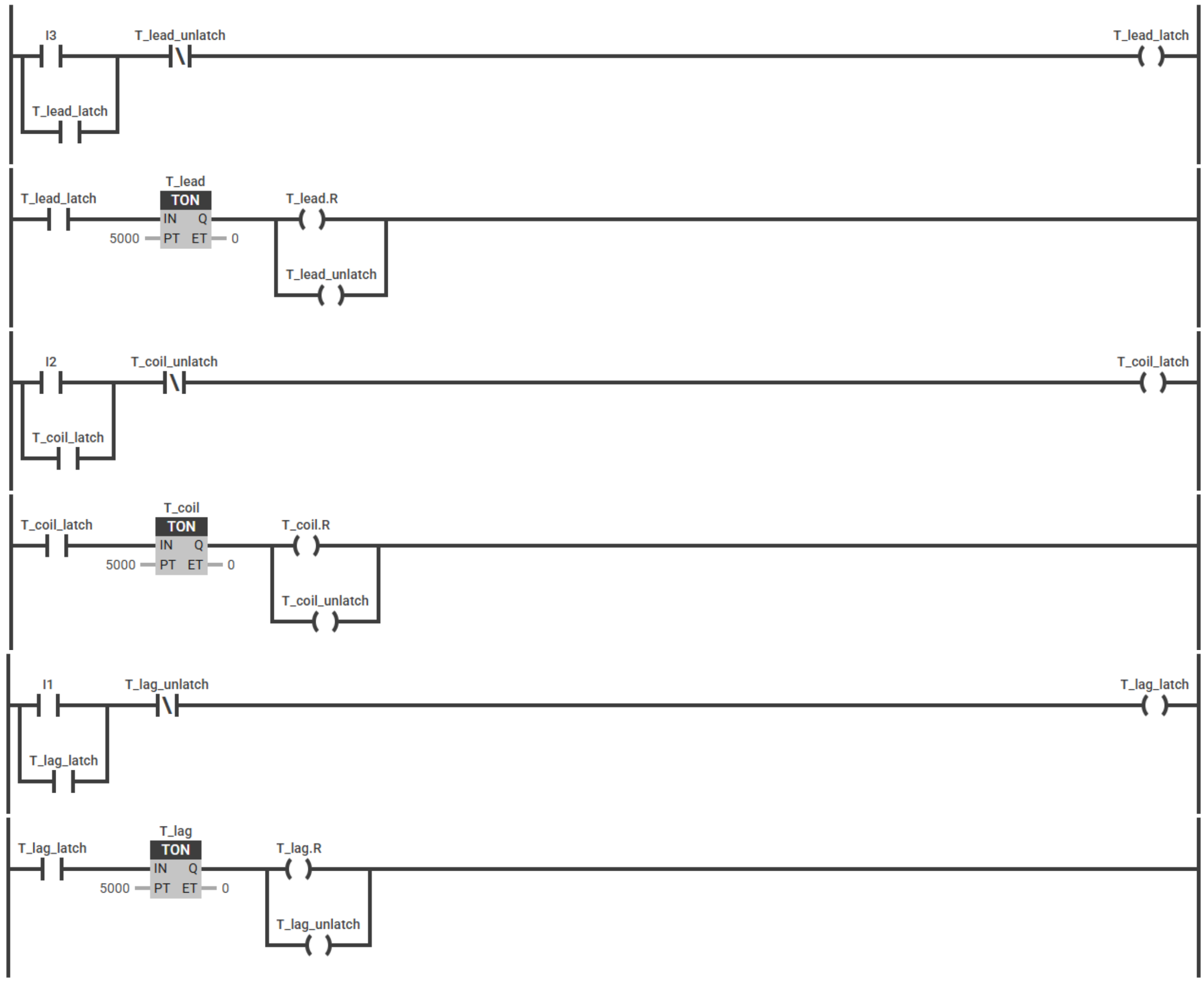
The three sensors can be replaced by three timers – i.e. the sensor output at the time of detection (front leg length, coil length and back leg length) would be replaced by the DONE output of a timer with a specific preset time (obtained through measurements and fine tuning). As such, the inputs defined for the three sensors can be reused as:
I5: Timer T1 DONE output (preset time for front leg length)
I6: Timer T2 DONE output (preset time for coil length)
I7: Timer T3 DONE output (preset time for back leg)

iv) If the timing of the machine's operations is to be controlled by timers in a PLC-based control program, explain how the timers would be integrated in a ladder logic diagram implementation of the finite state model. (Note: it is not necessary to construct a complete ladder logic diagram) [15%]

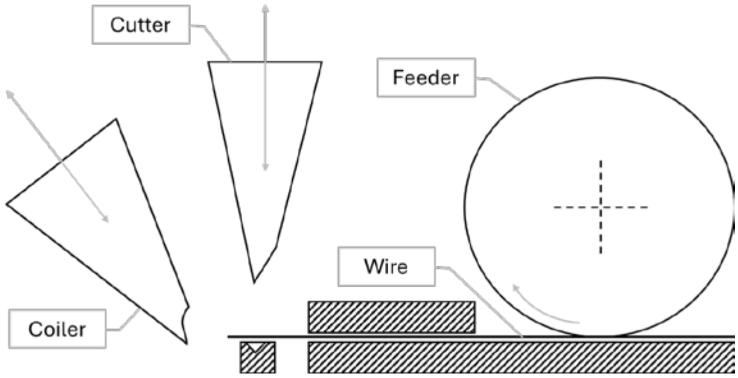
In the ladder logic diagram implementation of the finite state model, the three timers should be implemented and enabled/triggered by the appropriate state variables or other inputs. The DONE outputs of the timers should be implemented to enable/disable the appropriate state variables. The timers should be reset after every timeout.

An example of how the timers could be implemented in a ladder logic diagram implementation of the finite state model:

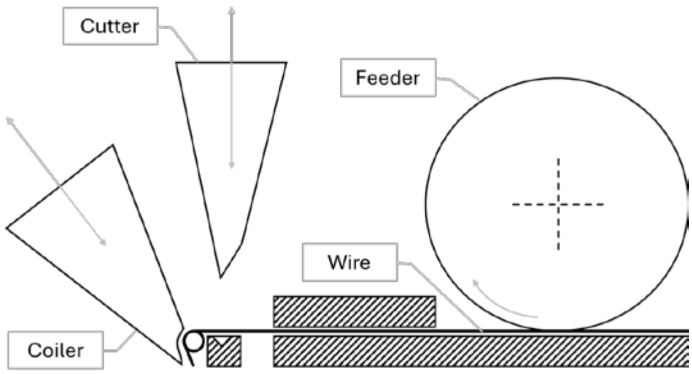



I3
T_lead_unlatch
T_lead_latch
T_lead_latch
T_lead_latch
T_lead
TON
IN
Q
5000
PT
ET
0
T_lead.R
T_lead_unlatch
I2
T_coil_unlatch
T_coil_latch
T_coil_latch
T_coil_latch
T_coil
TON
IN
Q
5000
PT
ET
0
T_coil.R
T_coil_unlatch
I1
T_lag_unlatch
T_lag_latch
T_lag_latch
T_lag_latch
T_lag
TON
IN
Q
5000
PT
ET
0
T_lag.R
T_lag_unlatch

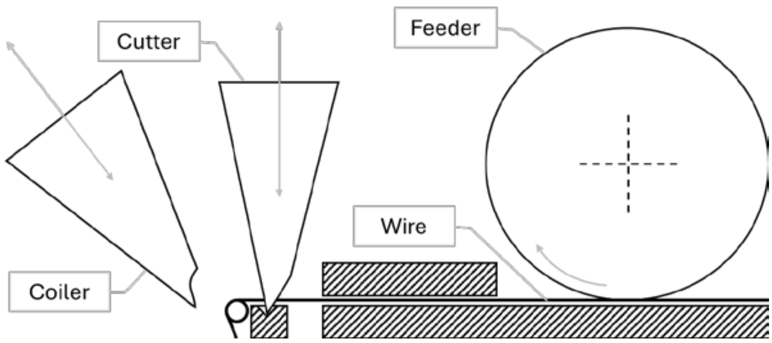
(a)



(b)



(c)



(d)

Figure 1: (a) A torsion spring; (b) A schematic, side-on view of a torsion spring forming machine with both the Coiler and Cutter mechanisms in the retracted position; (c) A schematic view the machine with the Coiler mechanism in the extended position and Cutter mechanism in the retracted position; (d) A schematic view of the machine with the Coiler mechanism in the retracted position and Cutter mechanism in the extended position.

Table 1: Inputs and outputs of the torsion spring forming machine.

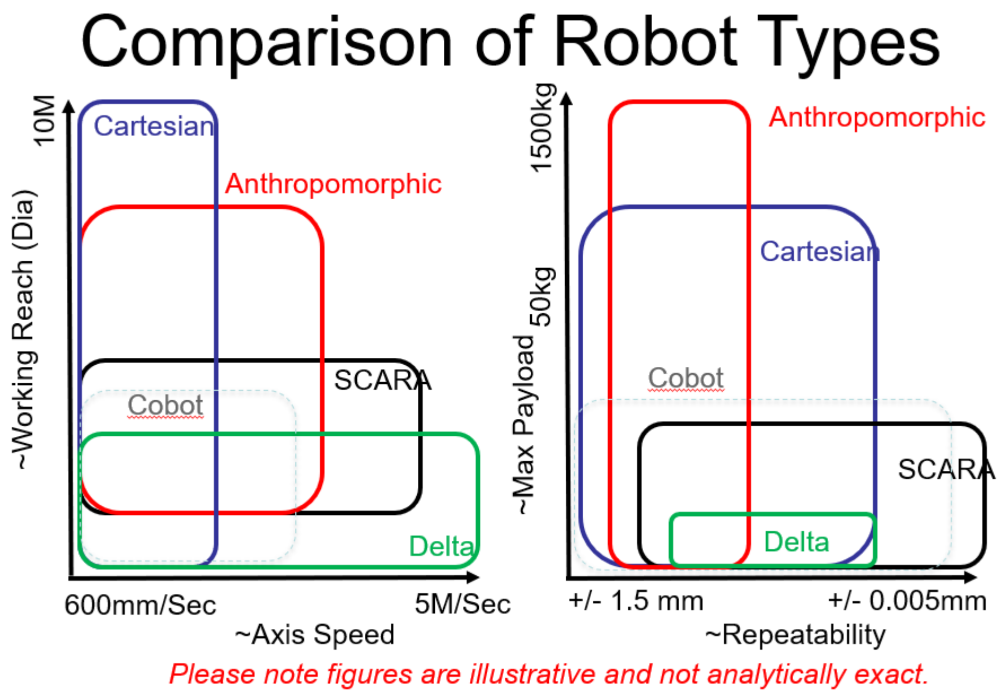
Inputs		**Outputs**	
I1	Coiler detected in retracted position	O1	Switches the Feeder motor on
I2	Coiler detected in extended position	O2	Switches the Coiler motor on to retract
I3	Cutter detected in retracted position	O3	Switches the Coiler motor on to extend
I4	Cutter detected in extended position	O4	Switches the Cutter motor on to retract
I5	Specified length of the front leg of the spring detected	O5	Switches the Cutter motor on to extend
I6	Specified length of the coil of the spring detected		
I7	Specified length of the back leg of the spring detected		
I8	Start button pressed		

Question 4

a) Robots are often used to support material handling in machining cells. Considering anthropomorphic, Cartesian and SCARA robot types, select the most suitable type of robot for each of the following scenarios. In each case, justify your selection.

i) The cell is to handle large, lightweight products that can be loaded into the two machines and the buffer in the same orientation. [15%]

The following figure from the lecture slides should be used to guide the selection of the appropriate robot type:



The cell is to handle large, lightweight products that can be loaded into the machines and buffer in the same orientation. As such, the robot does not have to move a heavy payload and a robot with fewer degrees of freedom would be suitable. Further, the large size of the products mean that the components of the cell must likely be further apart, i.e. the robot would require a larger working reach. No details are given regarding the speed or repeatability requirements of the cell.

Based on the requirements, a Cartesian robot would be the most appropriate robot type to select for this cell, because Cartesian robots (can) have a larger working reach than anthropomorphic and SCARA robots. Further, the additional degrees of freedom, larger payloads and higher speed of anthropomorphic and/or SCARA robots are not required in this cell.

ii) The cell is to handle a high volume of small parts and the machining operations have very short cycle times. [15%]

The figure above should again be used to guide the selection of the appropriate robot type.

The cell is to handle a high volume of small parts with short machining cycle times. As such, speed is a key consideration in the selection of an appropriate robot type. Further, the small parts are likely also lightweight, meaning that the payload of the robot is less of a concern. No details are given regarding the repeatability and working range requirements of the cell.

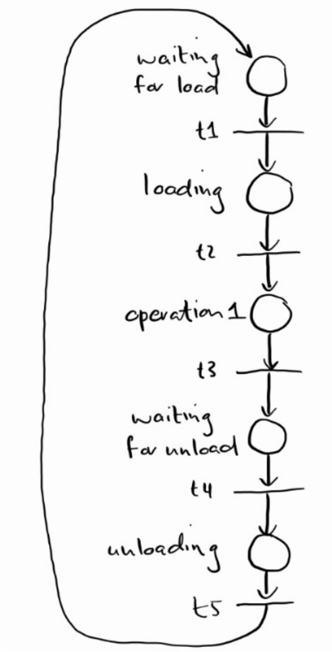
Based on the requirements, a SCARA robot would be the most appropriate robot type for this cell. SCARA robots are typically faster than anthropomorphic and Cartesian robots, while their lower payloads and smaller working reach are not detrimental to this cell's operation.

b) In the machining cell of Fig 2, products arrive on the input conveyor and are detected at the end of the conveyor by a sensor. The products first require a machining operation performed by Machine 1 and then a second machining operation performed by Machine 2. After the second machining operation, the products are only unloaded from Machine 2 and placed on the output conveyor if the conveyor has space (as detected by a sensor at the start of the output conveyor). The cell also includes a buffer for products between the two machining operations, which can hold up to eight products.

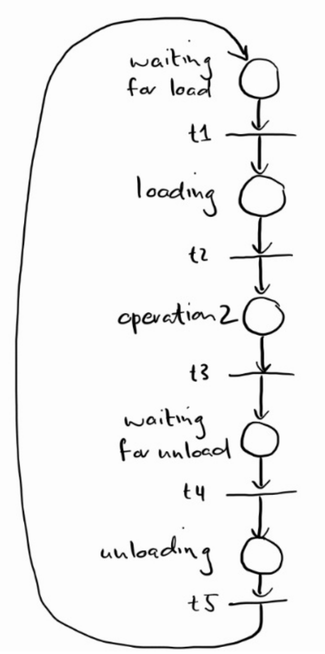
i) Draw three Petri Net models that represent the operations of the Robot, Machine 1 and Machine 2, respectively. Clearly label all elements and state any assumptions. [15%]

Robot:

Machine 1:

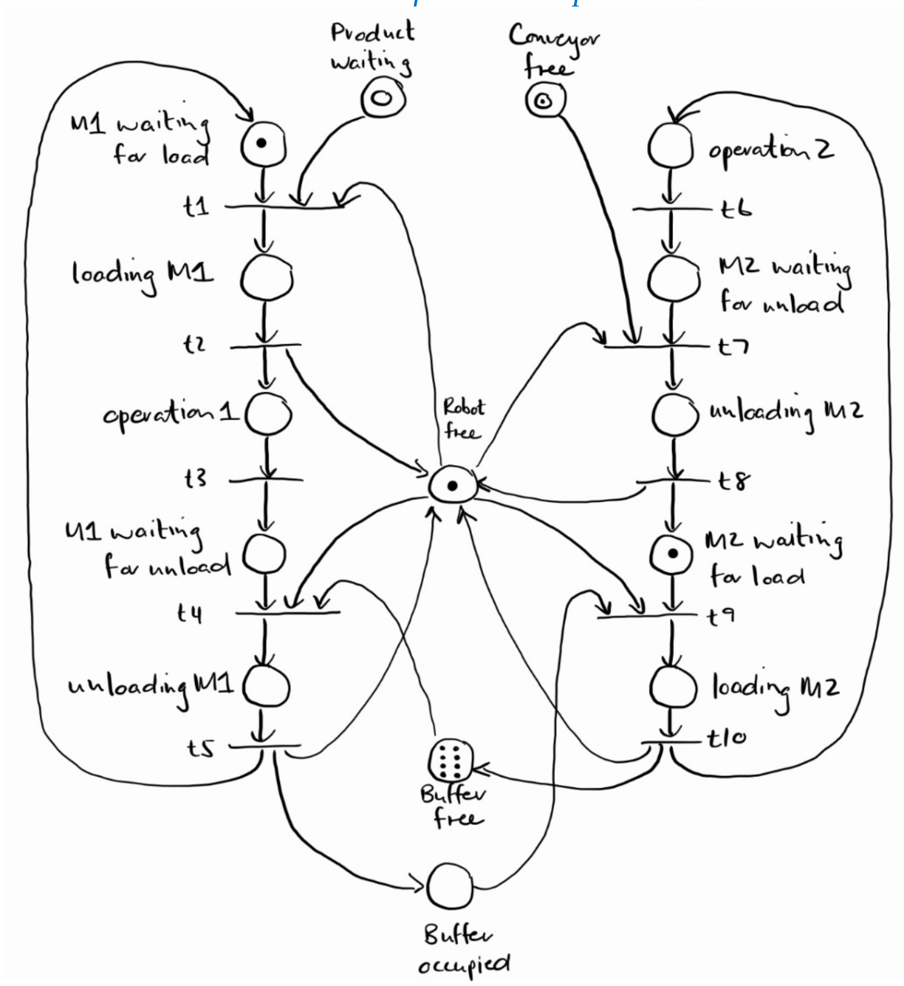


Machine 2:



ii) Draw a Petri Net model that represents the overall operations of the machining cell. Clearly label all elements and state any assumptions. [40%]

Petri Net model for overall operations:



c) Consider that a second robot is added to the machining cell of Figure 2, resulting in the cell layout shown in Figure 3.

i) Explain the benefits and constraints of making such an addition. [5%]

The addition of a second robot can improve the throughput of the machining cell and the cell's flexibility to handle different/additional operations or products in the future. However, the operations of the robots should be controlled/synchronised and continuously monitored to ensure that collisions are avoided within the overlapping workspace (i.e. the space around the product buffer).

ii) Indicate how the Petri Net model of the single-robot cell's operation developed in (b)(ii) should be adapted to represent the operations of the two-robot cell. State all assumptions. (Note: you do not need to draw the complete Petri Net model for the two-robot cell's operation) [10%]

In the two-robot cell, it should be assumed that Robot 1 would load and unload Machine 1, while Robot 2 would load and unload Machine 2. The Petri Net model developed for the Robot in (b)(i) should be split into two models – one for each robot. Both models must include a place indicating the availability of the robot. The model for Robot 1 will have places for "loading Machine 1" and "unloading Machine 1" and the model for Robot 2 will have places for "loading Machine 2" and "unloading Machine 2".

The Petri Net model for the cell's overall operation, developed in (b)(ii), should be adapted such that the Robot 1 model integrates with the Machine 1 model and the Robot 2 model integrates with the Machine 2 model.

To avoid the robots colliding, it may be assumed that only one robot can access the space around the buffer at a time. This constraint must be represented in the Petri Net model – a place that represents the availability of the buffer (space) can be added to the model, e.g. "buffer free". The "buffer free" place should be connected such that it enables/disables the transitions that lead to Robot 1 unloading Machine 1 and Robot 2 loading Machine 2, and that the transitions that indicate the end of these operations return a token to the place.

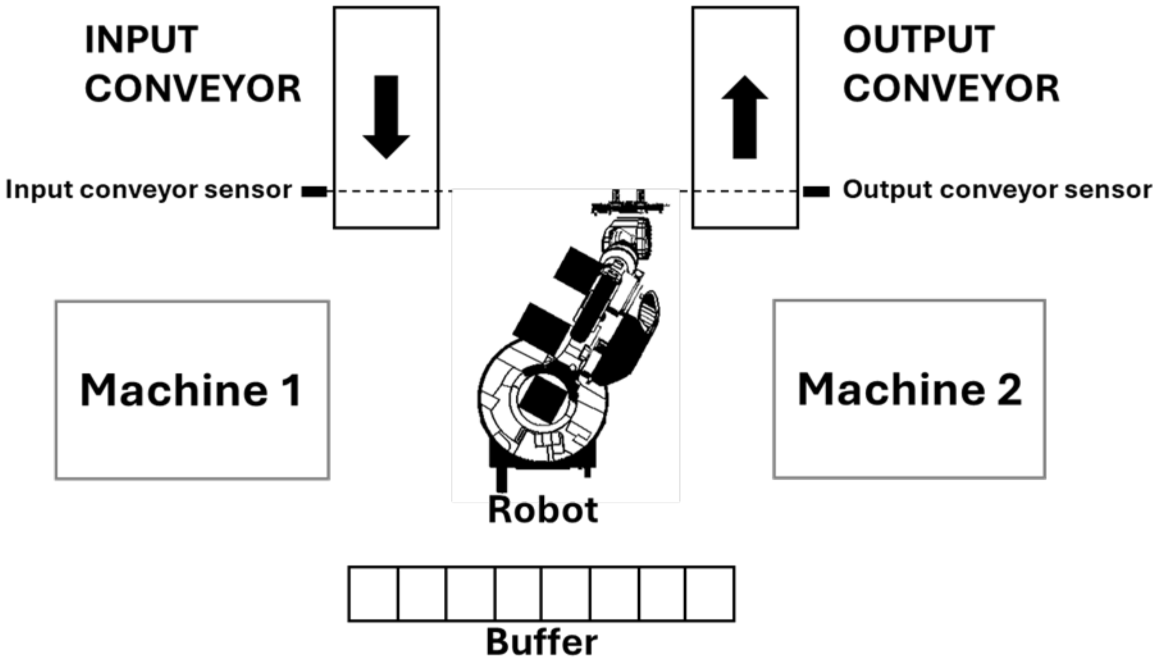


Figure 2: Layout of an automated machining cell.

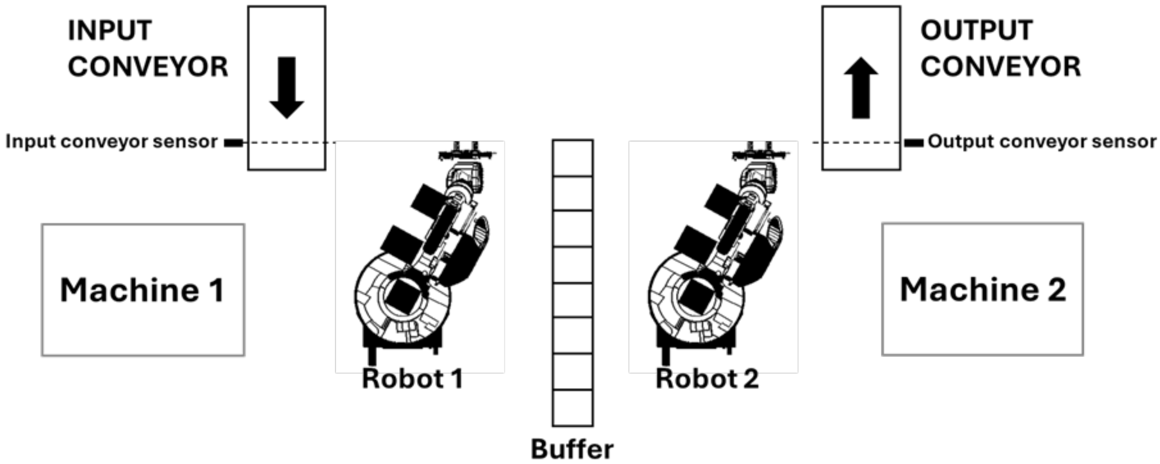


Figure 3: Layout of an automated machining cell with two robots